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WYLE LABORATORIES - RESEARCH STAFF TECHNICAL REPORT 64058-03

ENGINEERING EVALUATION OF SSME DYNAMIC DATA FROM ENGINE TESTS AND SSV FLIGHTS

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research REPORT

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ENGINEERING EVALUATION OF SSME DYNAMIC DATA FROM ENGINE TESTS AND SSV FLIGHTS

by

Research Staff

A final report of
work performed under contract NAS8-33508

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

February 1986

FOREWORD

This report was prepared by Wyle Laboratories, Scientific Services & Systems Group, for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. The work was performed under contract NAS8-33508, entitled "Dynamic Analysis of SSME Vibration and Pressure Data."

Mr. T. Coffin and Mr. W. L. Swanson, of the Wyle/Huntsville Research Department, served as Program Manager and Project Engineer, respectively, on this study. Messrs. T. Gardner, R. Dandridge, and Dr. J. Jong provided valuable contributions to SSME data analysis and component modeling tasks. Mr. W. C. Smith, MSFC/ED24 served as Contracting Officer's Technical Representative for the study. In this capacity he provided valuable assistance in the coordination of test evaluation activities and served as a focal point for defining task requirements and priorities.

ABSTRACT

This report summarizes an engineering evaluation of dynamic data from SSME hot firing tests and SSV flights. The basic objective of the study was to provide analyses of vibration, strain and dynamic pressure measurements in support of MSFC performance and reliability improvement programs. A brief description of the SSME test program is given and a typical test evaluation cycle reviewed. Data banks generated to characterize SSME component dynamic characteristics are described and statistical analyses performed on these data base measurements are discussed. Analytical models applied to define the dynamic behavior of SSME components (such as turbopump bearing elements and the flight accelerometer safety cut-off system) are also summarized. Appendices are included to illustrate some typical tasks performed under this study.

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SECTION I

EXECUTIVE SUMMARY

The Space Shuttle Main Engine (SSME) system and components have been and are presently undergoing extensive development and certification tests, at which time some 250 measurements are acquired, including vibration, strain, and dynamic pressure at critical engine locations. Limited engine data is also recorded during operational flights. Under the severe temperature, pressure, and dynamic environments sustained during operation, engine systems and components have been subject to malfunction and failure. Over the past 13 years of SSME development, 28 major component failures have occurred, causing extensive damage to engine hardware and test facilities, at considerable expense in cost and schedules. In addition, numerous off normal operations of a less severe nature have been observed.

Detailed analysis and evaluation of the dynamic measurements obtained is mandatory to permit quick assessment of engine component condition and the initiation of corrective measures when necessary. A wealth of dynamic data is available to support this effort. Efficient performance of this task is especially critical when considering the high test and launch rate in progress and the significant impact of dynamic evaluation results on test and launch turn-around time. Dynamic analysis, modeling and evaluation of SSME measurements and components have been performed by Wyle, under NASA contract NAS8-33508, in support of these efforts. This report documents the results of this investigation.

The basic objective of the effort was to provide detailed analyses and evaluation of vibration, dynamic pressure, and strain data available and being acquired during SSME tests. Additionally, analyses were performed on data obtained from Space Shuttle Vehicle flights. Statistical analyses were performed to characterize nominal and abnormal SSME component dynamic behavior under available operating conditions. Data banks representing component characteristics were generated and updated, and analyses performed to assess system response under actual and hypothesized operating conditions. This included update of the MSFC Diagnostic Data Base and application of the SSME Isospectral Automated Data Base System. A data base was also generated and updated in a format compatible with the Flight Accelerometer Safety Cut-Off System (FASCOS) filter characteristics to provide a basis for comparison of static test and flight results. FASCOS operational characteristics

have recently been defined statistically through system analysis and simulation, to permit assessment of the system logic.

The work was performed under three broad tasks, which are summarized as follows.

TASK I: Analysis, Evaluation, and Documentation of SSME Dynamic Test Results

Under this task Wyle performed analysis, evaluation and documentation of SSME dynamic test results. This task represented the mainstream of the contract effort and included data verification, analysis, evaluation, and documentation for each SSME ground test and additionally for SSV flight measurements. Results included definition of temporal and spectral characteristics observed. Subsynchronous, synchronous, and higher order spectral characteristics were summarized for engine components under all available operating conditions to characterize SSME component behavior. Full utilization of the SSME Isospectral Automated Data Base System was employed to provide informative data summaries. Strain measurements were analyzed as above, and improved strain data reduction procedures evaluated for subsequent strength and fatigue analysis. Oral presentation and written summaries were provided to document the results of each test and flight.

TASK III: Development and Documentation of Statistical Models of SSME Component Dynamic Behavior

Under this task Wyle developed, maintained, and updated the data base and statistical models of SSME component dynamic response measurements to provide characterizing profiles of observed parameter ranges, distributions, etc., under normal and abnormal operating conditions at available power levels. These models included wide-band root-mean-square values, narrow-band spectra, and band-pass results in the flight data format. Analytical models and computer schemes were applied to define the dynamic and statistical behavior of SSME components, such as bearing elements and the Flight Accelerometer Safety Cut-off Systems.

The above tasks are seen to be intimately related, since promising statistical/ analytical models may be immediately integrated into the SSME evaluation process. Also, data base statistics were immediately updated as test and flight measurements became available. It should be noted that the above evaluations were performed under extremely limited time constraints consistent with test and flight schedules. The extent of a given investigation varied widely depending on the specific measure-

ments acquired, whether or not observed engine operation was nominal, and the severity of any observed component malfunction of failure.

The following section presents an overview of the study. The SSME test/measurement program is briefly described. Dynamic evaluation considerations are discussed. SSME data base development and application tasks performed under this contract are summarized along with analytical/statistical modeling efforts. A list of engineering investigations recently performed in support of SSME dynamic evaluations is presented. This table indicates the wide diversity of engineering effort required in accomplishing contract objectives.

As with most test/evaluation programs, quick turnaround of investigative results was imperative to successful task accomplishment. These results were therefore provided directly to the MSFC COTR and cognizant Program personnel through informal data packages and presentations. A detailed discussion of each evaluation performed is given in the technical progress and interim reports provided under this contract. Several of these reports, addressing specific task evaluations, are included as Appendices for reference.

SECTION II

PROGRAM REVIEW AND SURVEY OF TASKS

2.1 Background

The Space Shuttle Main Engines (SSME) are required to operate under extreme temperatures with high fluid pressures and rotational pump speeds. Developmental work is presently in progress to uprate SSME performance, including engine certification at FPL (109%). The SSME and components have been subjected to extensive hot firing tests. Acceleration, dynamic pressure and strain data have been acquired during these tests and additionally from Space Shuttle Vehicle (SSV) flights. Analysis and evaluation of results obtained from SSME operation, to aid in the identification and resolution of sources of malfunction, were performed by Wyle Laboratories under NASA Contract NAS8-33508. Dynamic and statistical modeling to assess system behavior and component condition has also been accomplished.

This section presents an overview of the Space Shuttle Vehicle (SSV) system and SSME in particular. The SSME test program is briefly described, and a typical SSME test evaluation cycle is outlined. Some methods applied by Wyle to the assessment of acceleration, strain and dynamic pressure measurements are discussed. A recent investigation of the FASCOS system is also described.

2.1.1 The Space Shuttle Vehicle System

The SSV is composed of the Orbiter, an External Tank (ET), which contains the ascent propellant to be used by the Orbiter's three main engines, and two Solid Rocket Boosters (SRB). The Orbiter and SRBs are reusable; the ET is expended on each launch.

A Space Shuttle mission begins with installation of the mission payload into the Orbiter cargo bay. The SRBs and the SSMEs fire together at liftoff. The two SRBs are jettisoned after burnout -- about 45 kilometers (28 miles) high -- and recovered for reuse by means of a parachute recovery system. The SSMEs continue to burn until the Orbiter is just short of orbital velocity, at which time the engines are shut down and the ET jettisoned. During its return through the atmosphere, the tank will tumble, break up and be destroyed.

The orbital maneuvering system is used to attain the desired orbit and to make any subsequent maneuvers that may be needed during a mission. After orbital opera-

tions are completed, normally about seven days, deorbiting maneuvers are initiated. The Orbiter reenters the Earth's atmosphere at a high angle of attack. It then levels into horizontal flight at low altitude for an unpowered aircraft-type approach, landing at a speed of about 335 kilometers per hour (208 miles per hour).

2.1.2 The Space Shuttle Main Engines

The Orbiter vehicle main propulsion system consists of three SSMEs. The SSMEs are reusable, high-performance, liquid-propellant rocket engines with variable thrust. They are ignited on the ground at launch and operate in parallel, with approximately 500 seconds total firing duration. Each of the rocket engines operates at a mixture ratio (liquid oxygen/liquid hydrogen) of 6:1 and a chamber pressure of approximately 3000 psia to produce a sea-level thrust of 375,000 pounds and a vacuum thrust of 470,000 pounds. The engines are presently throttleable over a thrust range of 60 to 109 percent of the design thrust level. This provides a higher thrust level during liftoff and the initial ascent phase, and allows Orbiter acceleration to be limited to 3 g's during the final ascent phase. The engines are gimbaled ($\pm$10.5 degrees for pitch and $\pm$8.5 degrees yaw) to provide pitch, yaw, and roll control during the Orbiter boost phase.

Significant to meeting performance requirements is the use of a staged combustion power cycle coupled with high combustion chamber pressures. In the SSME-staged combustion cycle, the propellants are partially burned at high pressure and relatively low temperature in the preburners, then completely combusted at high temperature and pressure in the main chamber before expanding through the high-area-ratio nozzle. Hydrogen fuel is used to cool all combustion devices in contact with high-temperature combustion products. An electronic engine controller automatically performs checkout, start, mainstage, and engine shutdown functions. Major components of the SSME are illustrated in Figure 1. A more detailed view of the SSME power head is shown in Figure 2. This figure provides an indication of the complexity of the SSME turbomachinery.

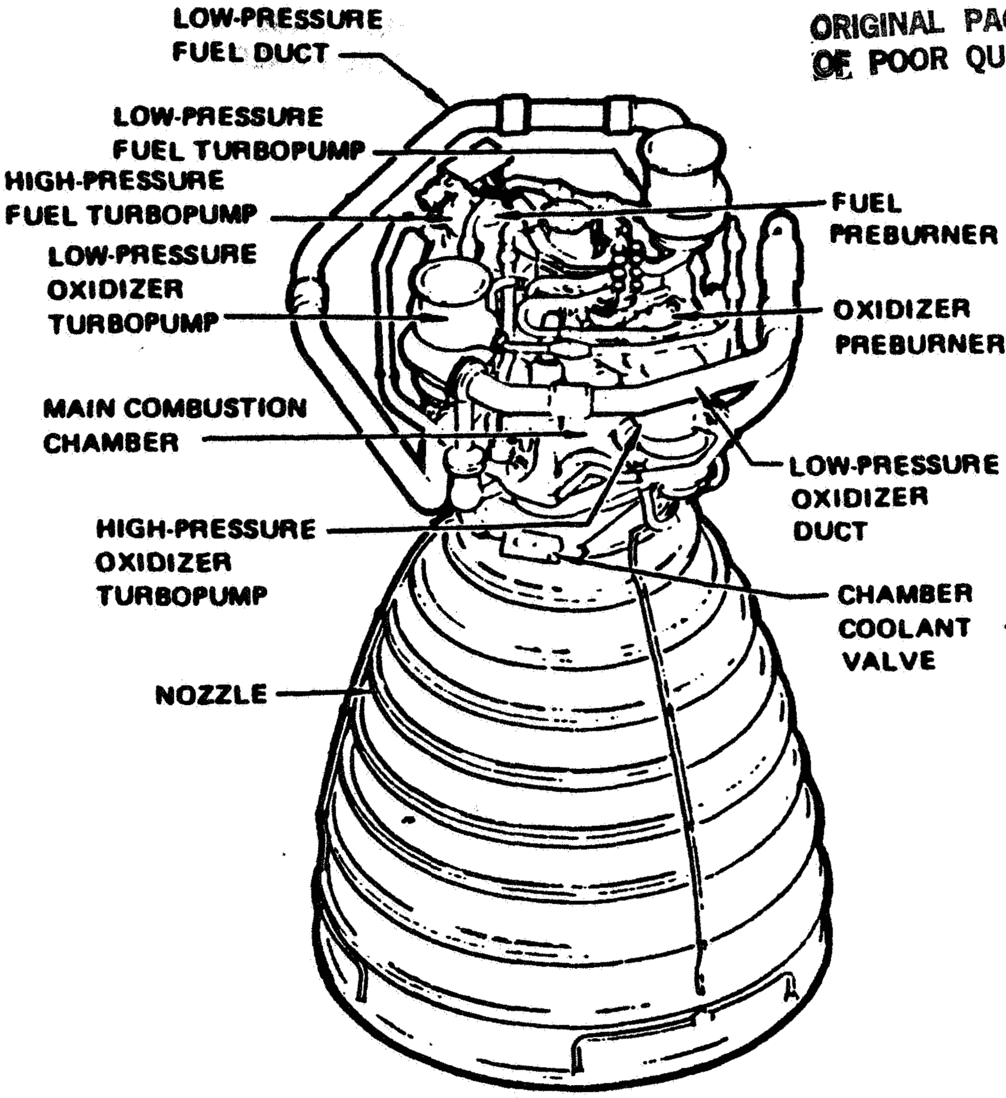

FIGURE 1. Space Shuttle Main Engine

2.1.3 SSME Development and Acceptance Testing

To validate system performance and ensure equipment reliability, the SSME and components have been and are presently undergoing extensive development and qualification tests. Testing of the engine and components is conducted at several NASA and contractor locations. Full scale engine test firings for development and flight acceptance are performed on two single-engine test stands at the National Space Technology Laboratories (NSTL), Bay St. Louis, Mississippi, and at one stand operated by Rockwell International near Santa Susana, California, with plans to include a development test stand at MSFC. In addition, main propulsion testing (MPT) is performed at NSTL on a stand designed to accommodate the Shuttle main propulsion system elements--the three-engine cluster, the ET, and the Orbiter systems.

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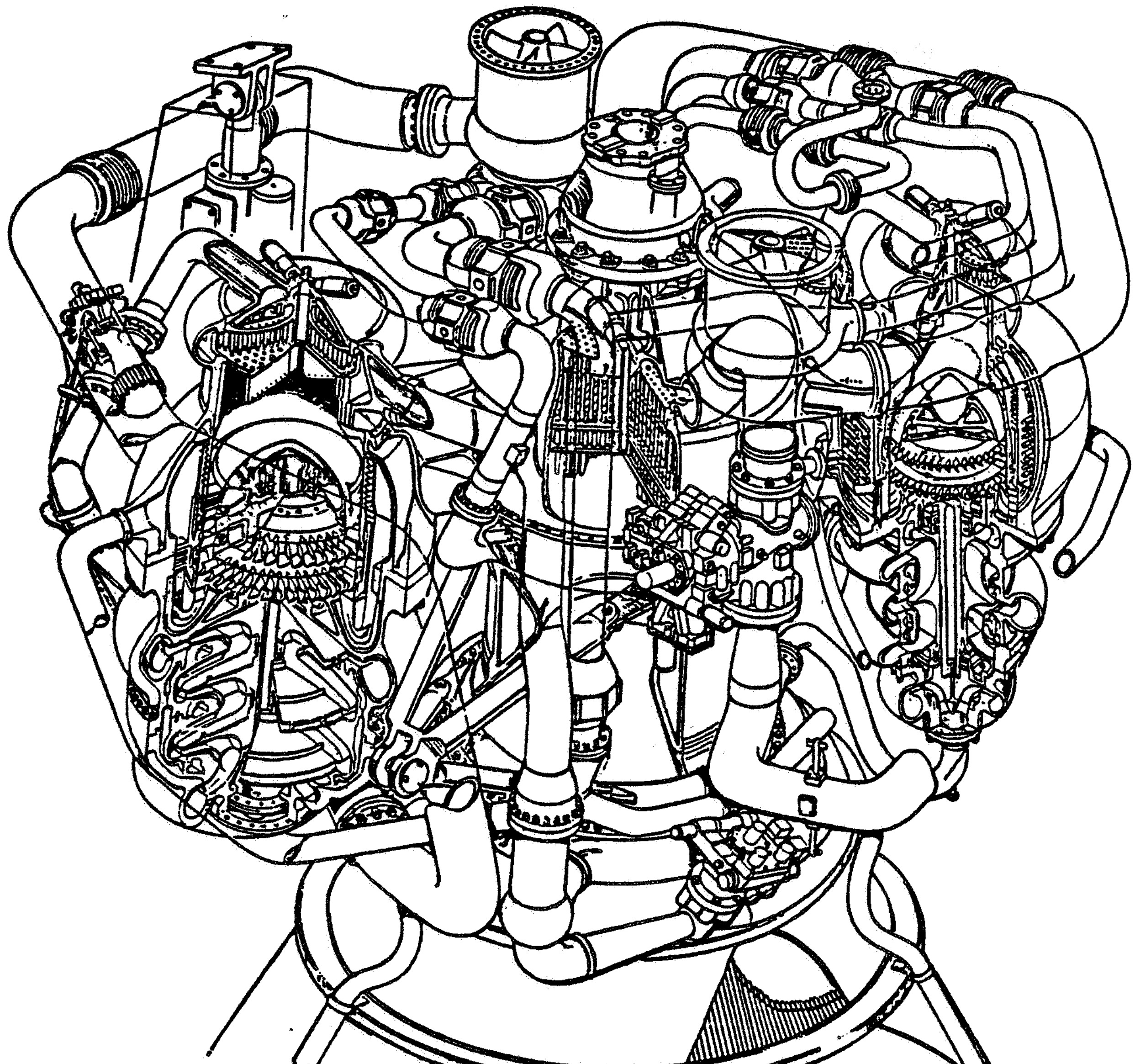

Figure 2. Space Shuttle Main Engine Power Head

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SSME INSTRUMENTATION

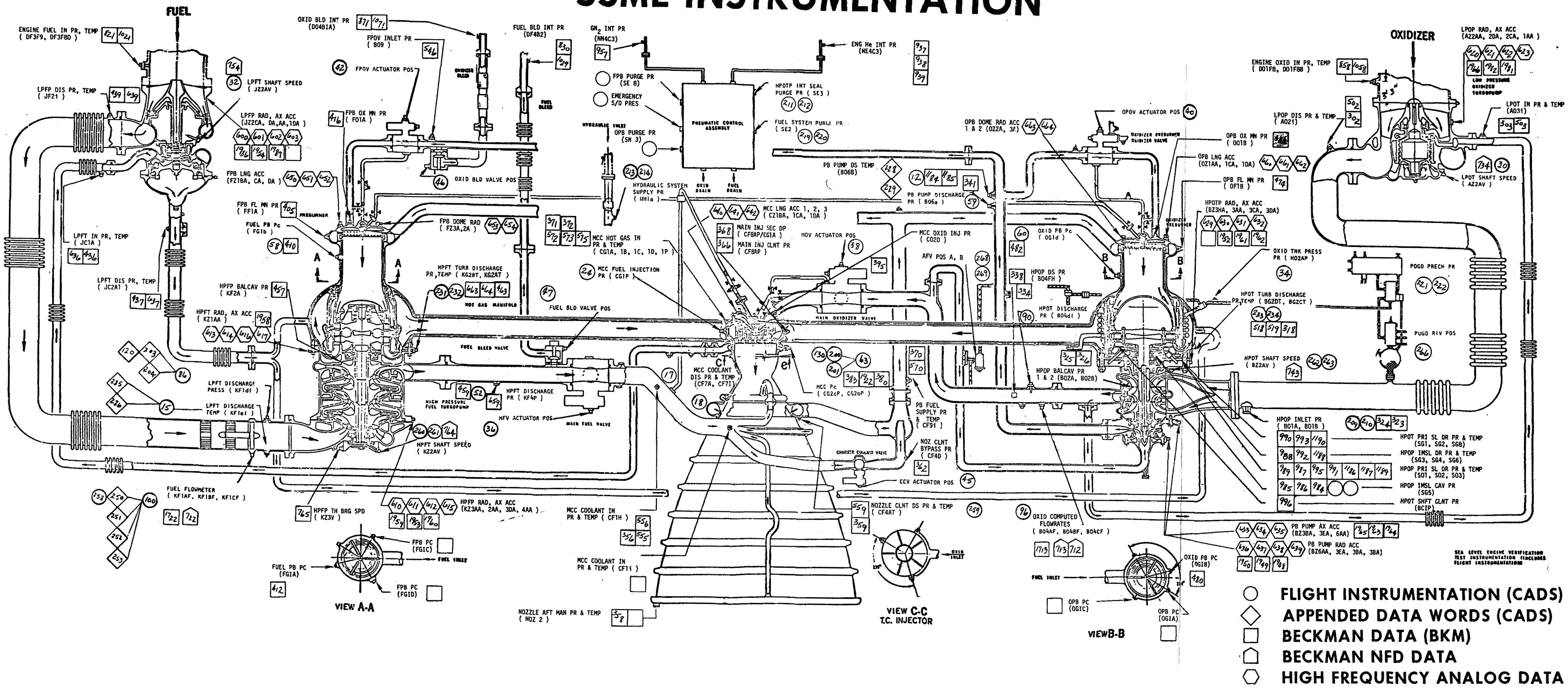

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Figure 3. Typical SSME Measurement Layout

FOLDOUT FRAME

2 FOLDOUT FRAME

Testing is being performed on a continuing basis. The length of a given test is dependent on specific test objectives and may run from several seconds to over 800 seconds. Tests are generally designed to satisfy multiple specific objectives, which fall into two broad categories; acceptance/certification firing of flight hardware and development testing directed towards design verification, performance and reliability improvement. Test operations are controlled by a computer called the Command and Data Simulator (CADS) which communicates with the engine, displays vital measurements for on-line observation/control and initiates pre- and post-test procedures.

Approximately 250 measurements are recorded on a given test including wide band vibration, dynamic pressure and strain at critical engine locations. Some of these measurements are utilized on-line as emergency cut-off indicators and all are recorded on magnetic tape for subsequent analysis and evaluation. Limited SSME vibration measurements are recorded on magnetic tape during SSV flights for evaluation with orbiter return. Typical dynamic measurements obtained during SSME operation are illustrated in Figure 3.

2.2 Engineering Evaluation of SSME Dynamic Data

2.2.1 Dynamic Analysis and Evaluation Considerations

Acceleration measurements are obtained at fuel and oxidizer turbopump locations during all test firings, providing an extensive vibration data base representing various turbopump builds under widely differing operating conditions. Additional measurements are obtained on a test-specific basis, depending on performance, structural integrity, or rotor dynamic characteristics under evaluation. For example, test series have been performed with some 80 strain measurements to support engine nozzle and injector dynamic stress evaluations. Recent firings have also been conducted with internally instrumented turbopumps to define component dynamic load and signature characteristics. Thus it is seen that the extent of the evaluation process varies widely from test to test, even though engine performance is nominal. In the event of anomalous performance or component malfunction, the extent of this process is increased significantly. Limited turbopump measurements are also obtained from the three SSMEs on each SSV flight. Data bandwidths available from SSV flight instrumentation differ from the wide-band capability used during ground testing, thus the need for generating a data base of filtered ground test measure-

ments to permit direct comparison with flight results. Typical engineering activities supported by Wyle in an SSME test evaluation cycle are summarized as follows.

Data evaluation and documentation:
- Data verification and validation
- Events analysis
- Temporal and spectral correlation with operating profile and machine dynamic characteristics
- Test/flight data summary

Analytical/statistical modeling and classification:
- Develop statistical models characterizing normal and abnormal behavior
- Update SSME diagnostic data base
- Establish and update engine cut-off redlines
- Develop and apply computer programs to define SSME component dynamic behavior

Failure investigation:
- Time/event correlations with other test parameters/observations
- Temporal and spectral comparison with structural dynamic and statistical models and associated failure modes
- Evaluation and recommendations of probable failure/effect scenarios, and means of resolution.

It should be noted that the above evaluation must be performed under extremely limited time constraints consistent with test and flight schedules. Also, the extent of a given evaluation depended on the specific measurements acquired and whether or not observed engine operation was nominal.

2.2.2 SSME Data Base Development and Application

Wyle personnel have been instrumental in the development, modification and application of the MSFC Diagnostic and Isospectral data base programs. These routines are used extensively in routine test evaluation and also in diagnostic investigations. The SSME diagnostic data base and software implemented in the last year has greatly facilitated the generation of quick-look performance summaries and comparisons for input to the SSME data reviews conducted immediately after each test, as well as the maintenance of historic statistical profiles. Figure 4, from Wyle TM 64058-01, illustrates a statistical summary of measurements obtained from the oxidizer

preburner pump during 141 test firings and the fuel turbopump flight data as of August 1985. These data represent measurements obtained under nominal engine operating conditions. Separate statistical definition is given for wide-band (composite) levels and the spectral levels at pump shaft speed (synchronous) and selected harmonics. Figure 5 illustrates cumulative and probability distributions characterizing the measurements. The cumulative distribution provides a useful tool for the quick-look assessment of test results with the historical distribution of measurements observed over a number of test firings, and also indicates the statistical risks implied by vibration level redlines.

A plot of the classical gamma distribution is included in these figures for reference, with parameters defined by

$$\Gamma^*(G) = (\lambda^{\alpha} / \Gamma(\alpha)) \int_0^G x^{\alpha-1} e^{-\lambda x} \, dx$$

where

$$\lambda = \bar{m}/\bar{\sigma}^2$$

$$\alpha = \bar{m}^2/\bar{\sigma}^2$$

and

$\bar{m}$ = sample mean

$\bar{\sigma}^2$ = sample variance

The application of classical statistical models is desirable for data characterization since this permits continuous statistical definition and manipulation from discrete measurement observations. Automated optimal function definition has also been developed for implementation in the diagnostic data base program. Software has been written to assess a wide class of competing functions including the Weibull, Gumbel and generalized lambda distributions.

STATISTICAL SUMMARY OF SSME VIBRATION DATA 16-MAR-84

Composite @109% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
A1	41	6.4	2.8	15.5	47	5.2	2.1	10.5	30	6.3	2.2	13.3
A2	44	5.3	2.3	11.0	52	5.3	1.6	10.0	24	5.5	1.9	9.0
A3	41	7.2	2.4	15.0	42	7.5	2.0	12.0	26	5.0	1.8	10.0
Combined	126	6.3	2.6	15.5	141	5.9	2.2	12.0	80	5.6	2.0	13.3

Synchronous @109% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
A1	40	2.9	1.8	7.6	44	3.2	2.0	8.6	31	3.5	1.9	8.5
A2	39	2.5	1.6	6.4	45	3.0	1.4	6.8	24	3.3	1.9	6.8
A3	37	2.5	1.6	7.6	40	2.8	1.5	8.9	24	2.5	1.8	9.1
Combined	116	2.6	1.7	7.6	129	3.0	1.7	8.9	79	3.1	1.9	9.1

TEST #'S A1244-350,A1353-355,A1357-362,A1364-388,A1390-392,A1394-398,A1401-408,A1410-436,A2195-305,A2307-332,A3047-112,A3114-152,A3154-160,A3169-172,A3174-181,A3184-223,A3225-232,

Composite @104% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	3.0	1.0	5.0	3	1.0	1.0	3.0	18	3.4	1.5	7.3

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @104% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	3.0	1.0	5.2	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Synchronous @104% Power Level

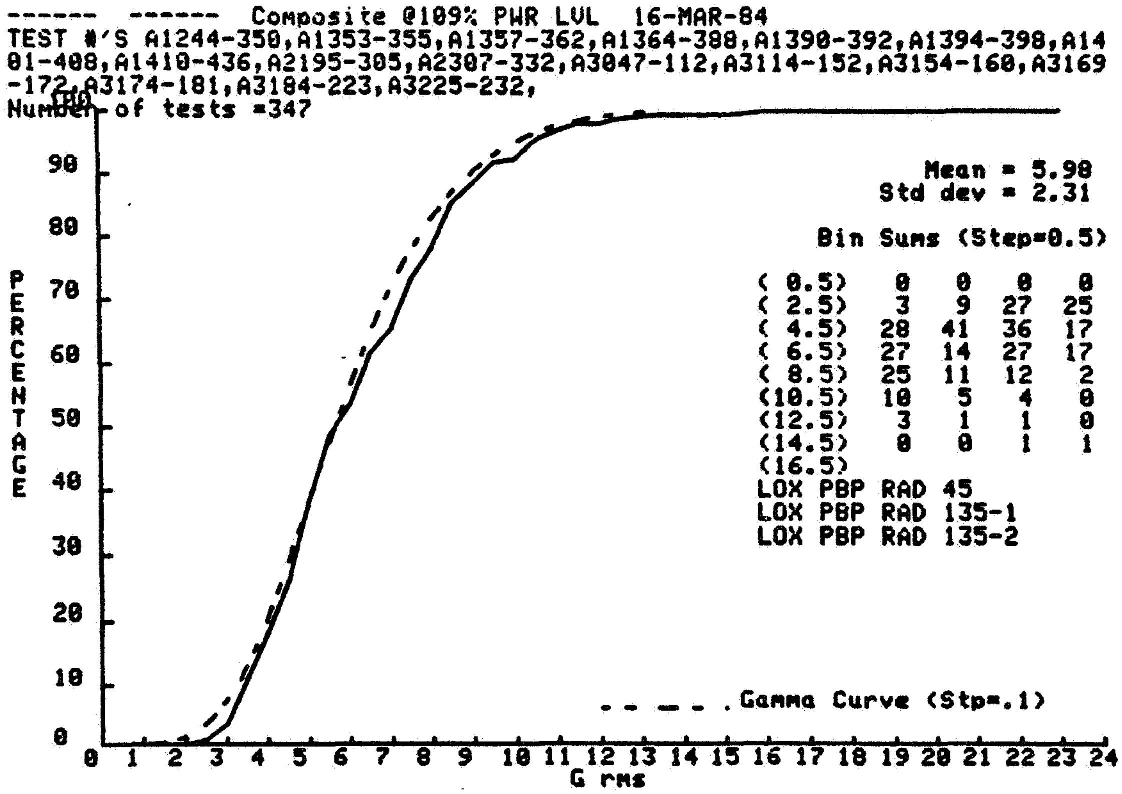
Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	2.7	1.0	4.7	3	1.3	1.0	2.3	18	2.6	0.8	3.0

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @104% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	2.5	1.0	5.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Figure 4. Statistical Summary of High Pressure Fuel and Oxidizer Pump Measurements for Ground and Flight Tests



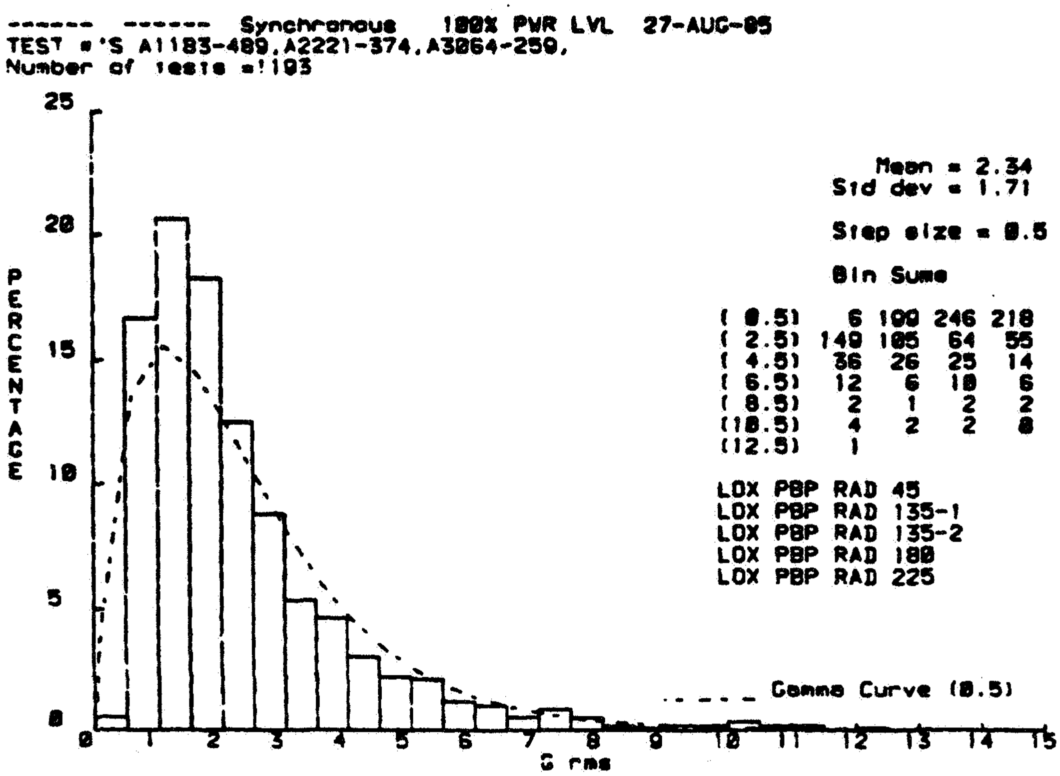


Figure 5. Cumulative and Probability Distribution Plots for a Selected Vibration Data Sample

In addition to the SSME diagnostic data base, the SSME Isospectral Data Base System was applied extensively. Historically, analog tapes were flown to MSFC, dubbed, reduced, and evaluated. Under the new system, spectra are extracted from the tapes every 0.4 second for each measurement throughout each test and stored at NSTL/Slidell. On command, the spectral data is telemetered to MSFC via satellite. Based on MSFC-developed software, these preprocessed data are then manipulated and printed to display isoplots, bandpass trends, engine speed, etc., on user command. As the diagnostic data base system has made test-to-test comparisons more efficient, the SSME isospectral analysis system has been a significant aid in the evaluation of time/amplitude/frequency trends within a test. In addition to the above preprocessed data, analog tapes are also obtained by MSFC for special-purpose time and frequency domain analysis. Modification of the Isospectral data base is under evaluation to include transmission of the Fourier coefficients (amplitude and phase) as well as PSD samples. This will permit immediate access to the vibration time history for detailed analysis, by straightforward inverse transformation.

Figure 6 is an example of an isoplot representing a high pressure fuel turbine measurement throughout test 902-378. A frequency band of 60 Hz to 1310 Hz and 1310 to 2560 Hz was selected and a spectrum plotted every 8 seconds. The displayed amplitude range is selectable, permitting clear representation of major spectral peaks or identification of low level spectral components. Interpretation obviously requires correlation with engine speed and other parameters. Figure 7 illustrates the root-mean-square acceleration time history composite, synchronous and selected harmonics for the same measurement. This time history is synthesized from the stored isospectral data by integrating over the PSDs obtained each 0.4 second during the test.

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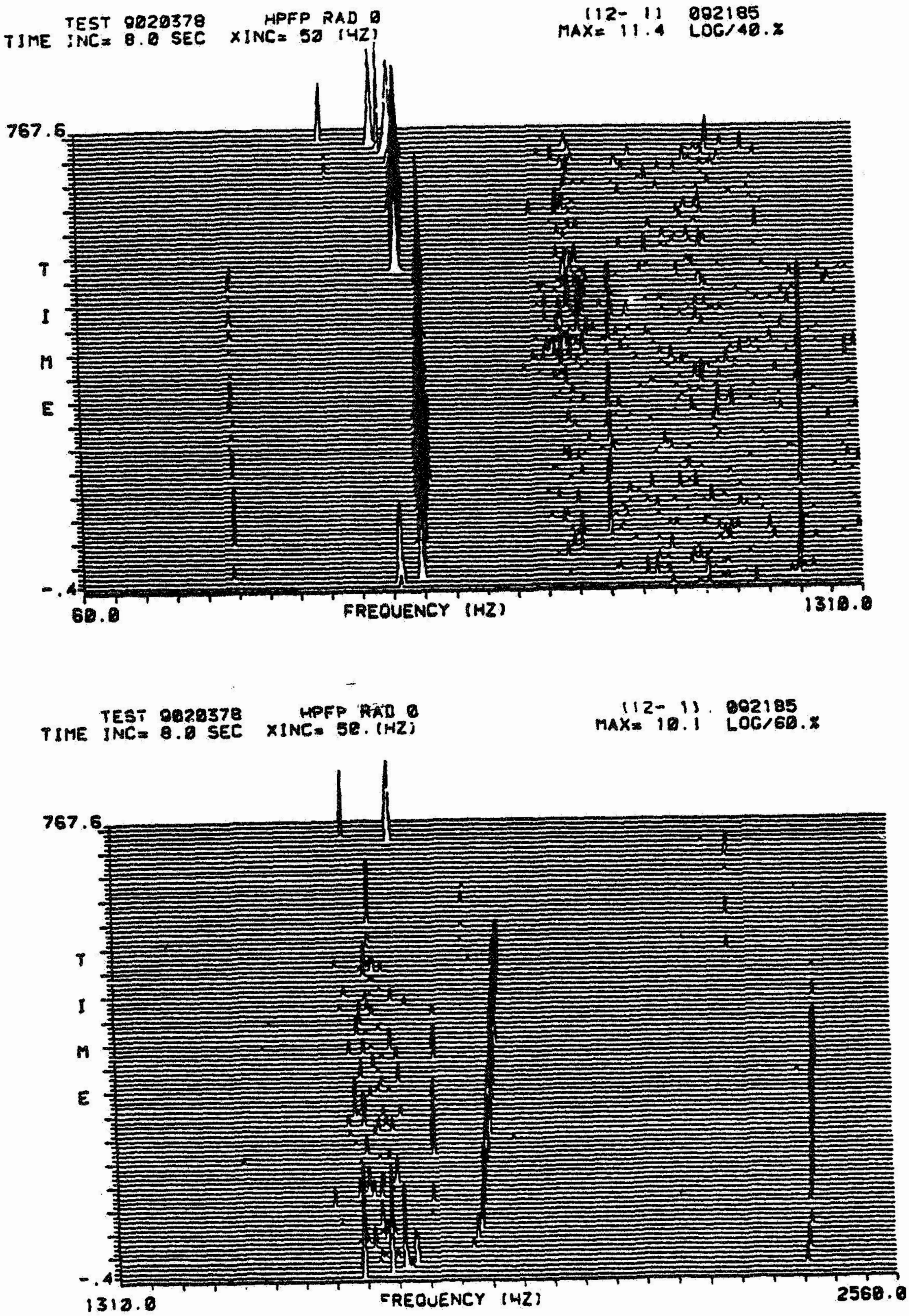


Figure 6. Isoplot of a High Pressure Fuel Turbopump Measurement

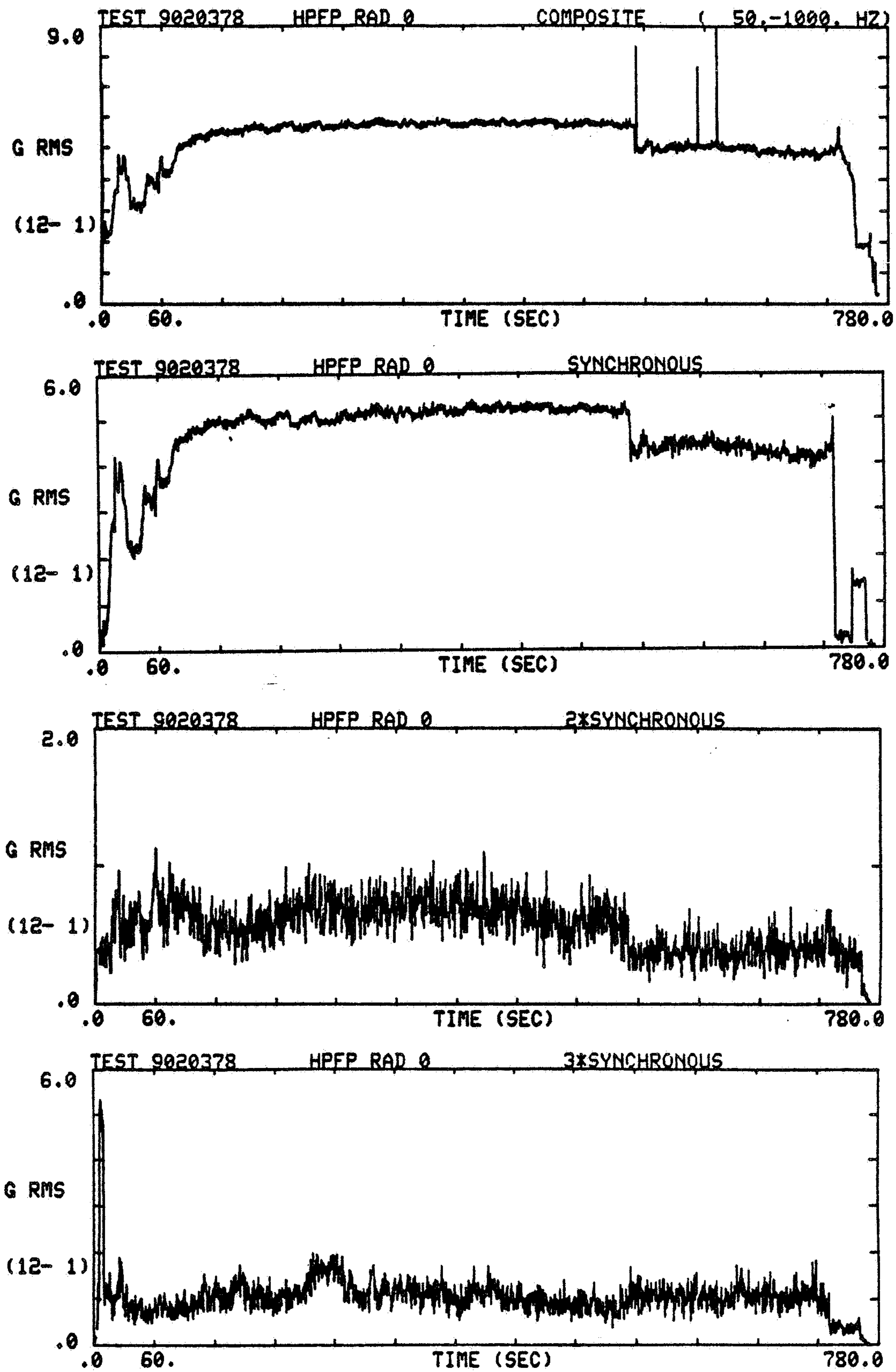


Figure 7. Acceleration Time History of a High Pressure Fuel Pump Measurement and Selected Harmonic Contributions

A sample PSD for the same measurement is illustrated in Figure 8. An "Anomalous Frequency" routine was developed to track spectral components within a selected frequency band and relate these to the synchronous behavior. Figures 9 and 10 illustrate the output of the procedure in the selectable frequency bands of 200-400 Hz and 1700-2000 Hz. Another feature of the Isospectral Data Base Program is the cumulative speed analysis routine. Certain components on the SSME respond more strongly when exposed to a narrow speed range. Software was developed to track and evaluate the total time a particular serial number pump has accumulated in each speed range for a given test or series of tests. An example plot and tabulated values for two recent tests (A1-377 and A1-378) are shown in Figure 11.

2.2.3 Special Considerations in Dynamic Strain Assessment

Wide band strain measurements have generally been characterized in terms of power spectra and rms time histories. In special cases (such as a LOX injector post fatigue evaluation supported under this contract) peak strain distributions were estimated. More refined cycle counting techniques appeared desirable to characterize dynamic strain measurements. A cursory review of the experimental literature on high cycle fatigue was therefore performed.

Miles' classical relation for fatigue under random vibration is based on an assumed distribution of stress or strain peaks. In a complex time history, consideration of adjacent peaks (and valleys) only can mask wide variations (the range) of the dynamic stress or strain incurred. A number of empirical cycle counting techniques have therefore been developed by researchers to better account for the ranges of stresses in a complex wave. When considering that damage has been shown to be roughly proportional to the sixth power of the strain range, importance of cycle counting and range definition techniques is underlined.

The objective of all cycle counting methods is to relate the effect of a complex load, stress or strain time history to material fatigue properties obtained under simple cyclic loading conditions. "Overall range" counting methods have been shown to correlate more highly with observed fatigue life than simple peak value distributions.

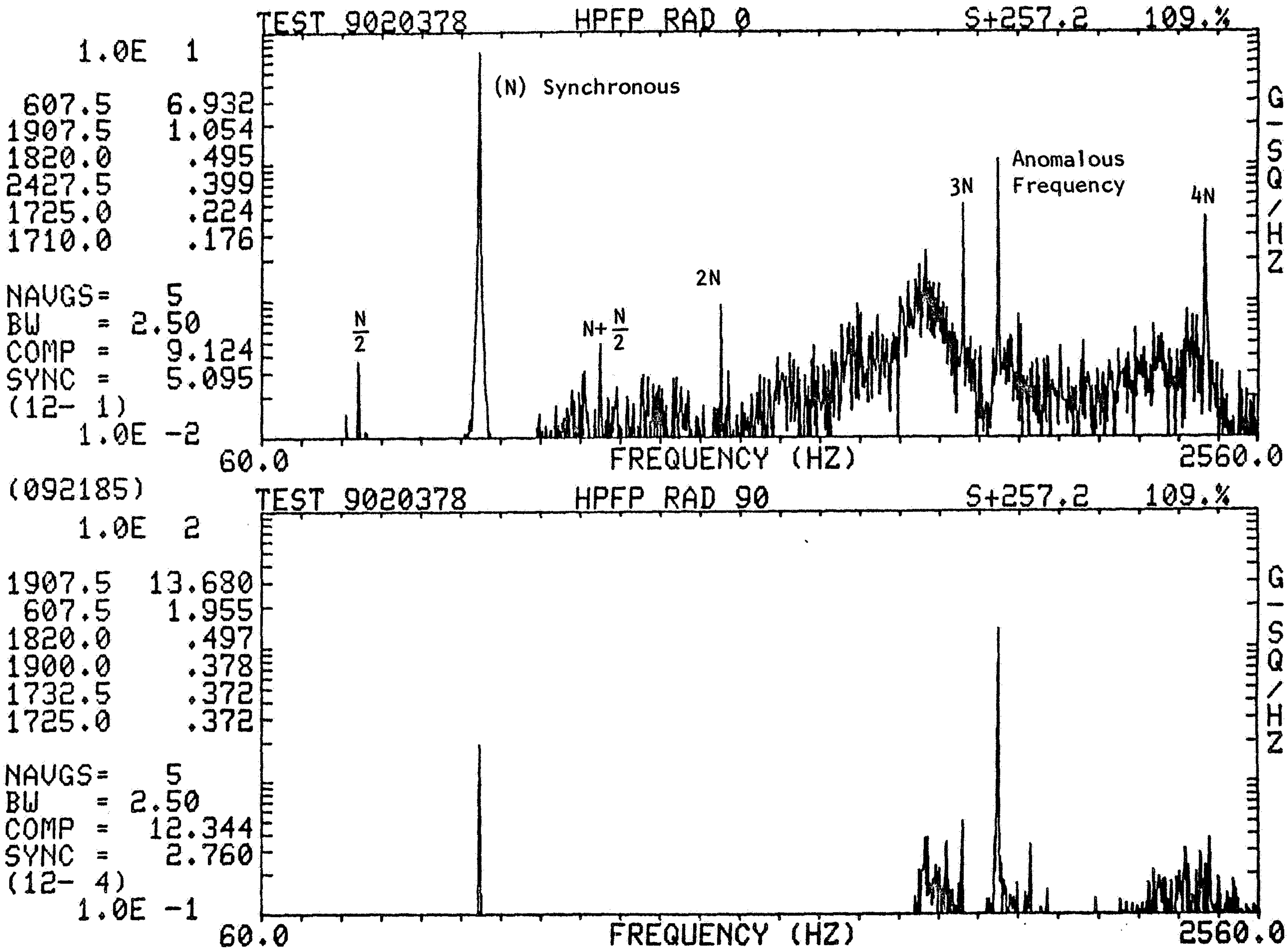


Figure 8. Power Spectral Density of a High Pressure Fuel Turbopump Measurement

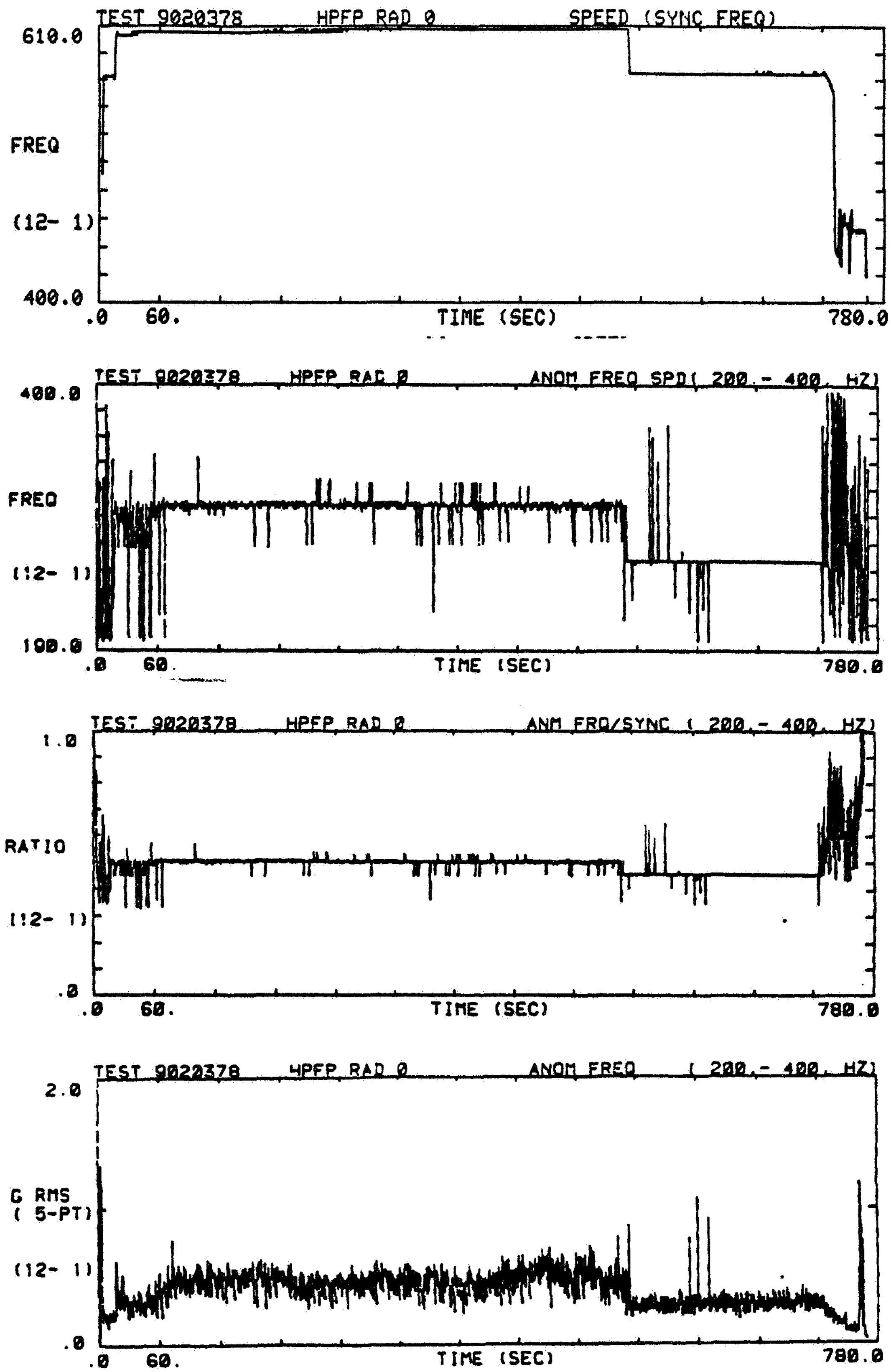


Figure 9. Sample of Anomalous Frequency Routine Output (200-400 Hz)

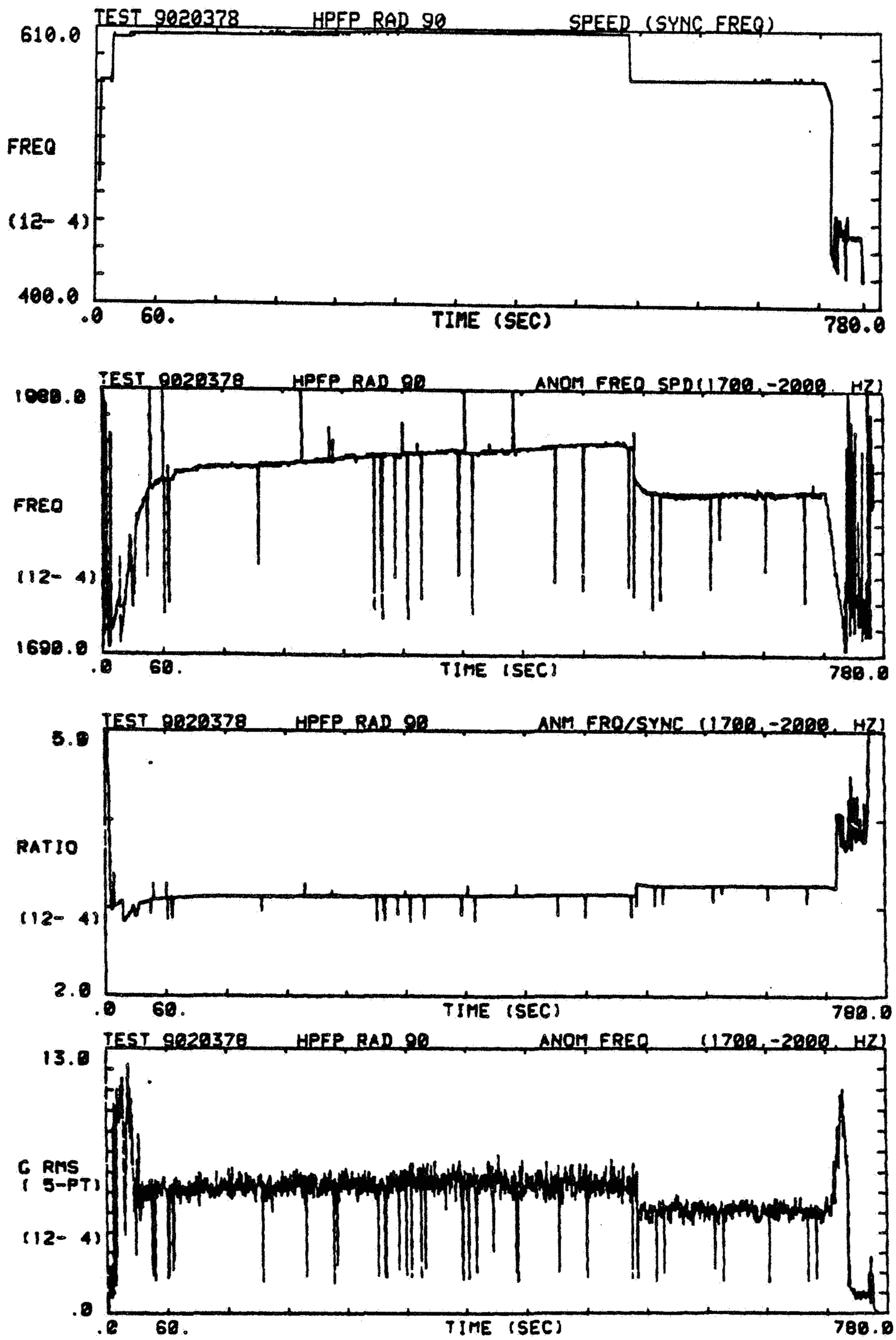
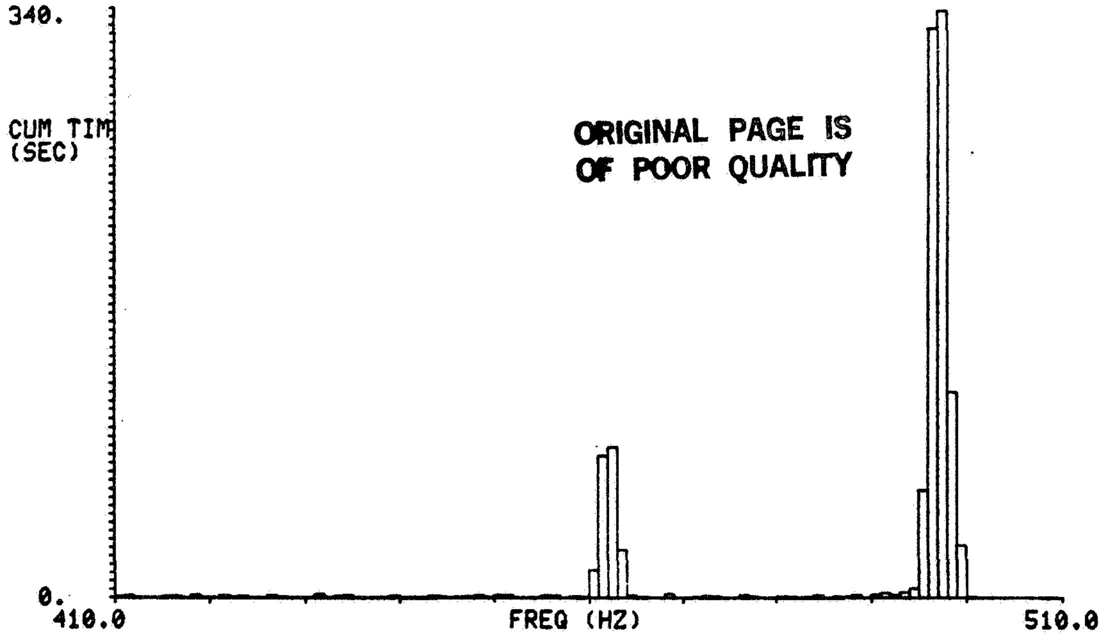


Figure 10. Sample of Anomalous Frequency Routine Output (1700-2000 Hz)

9020377 9020378

HPOTP SPEED BIN INCREMENT= 1.0 HZ



9020377 9020378
HPOTP SPEED
BIN INC= 1.0 (HZ)

FREQ	RPM	TIME
40.0	2400.	1.2
45.0	2700.	.4
50.0	3000.	.4
70.0	4200.	1.6
75.0	4500.	.8
76.0	4560.	.4
83.0	4980.	.4
96.0	5760.	.8
112.0	6720.	1.2
132.0	7920.	.4
133.0	7980.	.8
137.0	8220.	.4
139.0	8340.	.8
145.0	8700.	.8
146.0	8760.	.4
150.0	9000.	.8
155.0	9300.	.4
156.0	9360.	.4
158.0	9480.	.4
168.0	10080.	.4
190.0	11400.	.4
192.0	11520.	.8
193.0	11580.	.4
204.0	12240.	.4
211.0	12660.	.4
212.0	12720.	.4
213.0	12780.	.4
215.0	12900.	.4
226.0	13560.	.8
234.0	14040.	.4
248.0	14880.	.4
251.0	15060.	.4
253.0	15180.	1.2
255.0	15300.	.4
256.0	15360.	.4
260.0	15600.	.4
264.0	15840.	.4
269.0	16140.	.4
278.0	16680.	.4
280.0	16800.	.4
281.0	16860.	.4
283.0	16980.	.8
286.0	17160.	.4
294.0	17640.	.4
298.0	17880.	.4
305.0	18300.	.4
310.0	18600.	.4
311.0	18660.	.8
313.0	18780.	.8
314.0	18840.	.8
316.0	18960.	1.2
318.0	19080.	.4
319.0	19140.	1.2
320.0	19200.	.4
321.0	19260.	.8
322.0	19320.	1.2
325.0	19500.	1.2
326.0	19560.	2.0
327.0	19620.	11.2
328.0	19680.	19.6
329.0	19740.	8.0
330.0	19800.	2.0
331.0	19860.	.8
335.0	20100.	1.6
336.0	20160.	2.0
338.0	20280.	1.2
339.0	20340.	.8
340.0	20400.	2.0
341.0	20460.	2.0
342.0	20520.	1.6
343.0	20580.	.8
344.0	20640.	.4
345.0	20700.	.8
346.0	20760.	1.6
351.0	21060.	2.0
352.0	21120.	.4
353.0	21180.	1.2
354.0	21240.	.8
355.0	21300.	.4
358.0	21480.	.8
359.0	21540.	1.2
361.0	21660.	.8
363.0	21780.	1.2
365.0	21900.	.8
366.0	21960.	.8
369.0	22140.	1.6
373.0	22380.	.8
374.0	22440.	.8
375.0	22500.	.4
376.0	22560.	1.6
381.0	22860.	2.0
383.0	22980.	.8
384.0	23040.	1.2
388.0	23280.	2.0
391.0	23460.	.4
392.0	23520.	1.6
394.0	23640.	.4
396.0	23760.	1.2
398.0	23880.	1.6
399.0	23940.	1.2
403.0	24180.	1.6
404.0	24240.	.8
406.0	24360.	.4
407.0	24420.	1.2
410.0	24600.	.8

9020377 9020378
HPOTP SPEED
BIN INC= 1.0 (HZ)

411.0	24660.	1.2
415.0	24900.	.8
416.0	24960.	.8
418.0	25080.	1.6
421.0	25260.	1.2
422.0	25320.	.4
423.0	25380.	.8
426.0	25560.	1.2
427.0	25620.	.4
431.0	25860.	2.0
433.0	25980.	.8
434.0	26040.	1.2
438.0	26280.	.4
439.0	26340.	1.2
441.0	26460.	.4
442.0	26520.	.4
443.0	26580.	1.2
444.0	26640.	.4
446.0	26760.	.4
447.0	26820.	.8
448.0	26880.	1.6
449.0	26940.	.4
450.0	27000.	1.2
451.0	27060.	1.2
453.0	27180.	.4
454.0	27240.	.4
455.0	27300.	1.6
456.0	27360.	1.6
458.0	27480.	.8
459.0	27540.	.8
460.0	27600.	16.8
461.0	27660.	84.4
462.0	27720.	88.8
463.0	27780.	28.4
464.0	27840.	1.6
465.0	27900.	.4
466.0	27960.	.4
468.0	28080.	2.4
471.0	28260.	.4
472.0	28320.	1.2
473.0	28380.	.8
476.0	28560.	1.2
477.0	28620.	.8
480.0	28800.	.8
481.0	28860.	.8
482.0	28920.	.4
483.0	28980.	.4
484.0	29040.	1.6
486.0	29160.	.8
487.0	29220.	.4
488.0	29280.	1.6
490.0	29400.	1.2
491.0	29460.	2.8
492.0	29520.	1.6
493.0	29580.	3.2
494.0	29640.	5.6
495.0	29700.	64.0
496.0	29760.	327.6
497.0	29820.	339.4
498.0	29880.	120.0
499.0	29940.	31.6
500.0	30000.	.4

Figure 11. Sample of Cumulative Speed Analysis

Three cycle counting techniques and associated computational algorithms appear most prominent in the literature for fatigue evaluation of complex strain (stress) time histories. These are known as the range-pair, Rainflow (or hysteresis loop closure) and ordered overall range (or racetrack) methods. These three procedures yield virtually identical results. Computational schemes for implementation of these methods were also obtained from the references. These techniques permit significant data compression, in that only major strain excursions need be retained to characterize fatigue growth. The strain ranges generated as above are generally used concurrently with a fatigue analysis. However, the techniques may also be used directly in the data reduction procedure to generate strain range spectra depicting the number of occurrences as a function of strain range (a probability density approximation). Statistical definition of strain range spectra per event (such as engine startup) or per unit time (during constant power operation, for example) should constitute a valuable component fatigue life estimation tool.

2.3 Analytical/Statistical Modeling

The above discussion illustrates some capabilities of the SSME data base systems and software. Wyle personnel have made extensive use of this capability to define component test heritage and response characteristics. Numerous dynamic modeling investigations have also been conducted ranging from quick-look failure evaluations to extensive computer simulations of system behavior. As an example of these efforts, we summarize a recent evaluation of the SSME Flight Accelerometer Safety Cut-Off System (FASCOS) logic. Some additional investigations are described in the Appendix.

Certification of the SSME at full power level (109%) is in progress. Implementation of the FASCOS system is an essential element of the certification program. The FASCOS is a vibration based engine condition monitor. The system continuously monitors accelerations measured on the SSME turbopumps during engine operation. Based on these measurements and assigned vibration "redlines," the FASCOS and engine control computer determine the "operational health" of each engine through a series of nonlinear operations on the vibration signals and a voting protocol. The outcome of the decision process (run/cut-off) is highly dependent on the redline values assigned to the FASCOS comparator and the (statistical) behavior of the monitored signals. For this reason an intensive analysis/simulation effort was

recently initiated by MSFC to define the FASCOS decision process as a guide to the assessment of redlines with respect to mission success and safety. Wyle performed analytical modeling and computer simulations in support of this challenging and significant task.

A functional schematic of the FASCOS logic is illustrated in Figure 12. Three accelerometer signals are processed simultaneously to perform the required turbopump operational condition assessment. Major elements of the system are

- A filter/detection stage
- A comparator with time delay
- A voting protocol based on the simultaneous state of the three comparator outputs.

The filter/detection stage is shown in more detail in Figure 13. This circuit consists of:

- Band-pass filter (approximately 50 Hz-1 KHz)
- Square-law detector
- Exponential low-pass filter
- Square-root detector
- Second low-pass filter.

It is seen that this nonlinear sequence of operations transforms the (possibly) wide-band vibration input into a slowly varying "weighted RMS" signal output which is fed to the comparator.

The comparator is essentially a voltage gate with an adjustable threshold level and time delay required to activate the "switch." The threshold level defines the vibration redline which must be exceeded to initiate an output. The time delay precludes a threshold exceedance indication due to spurious noise sources. Transfer characteristics of the FASCOS comparator are illustrated in Figure 14. The output is seen typical of a random telegraph signal. The length of each pulse represents the (random) persistence time (minus delay) of the input signal above the redline threshold level.

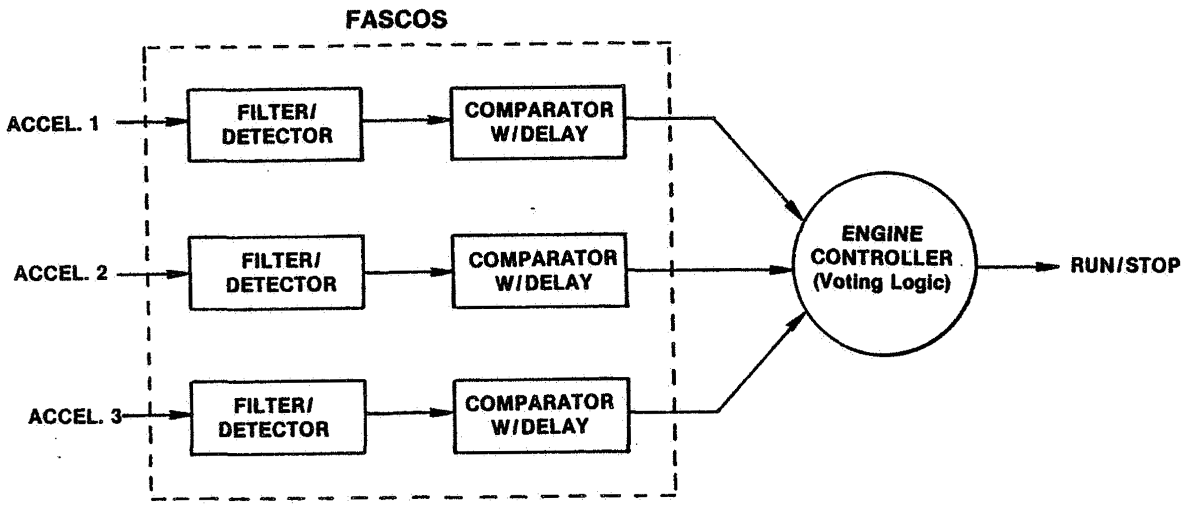


Figure 12. Functional Schematic of the FASCOS

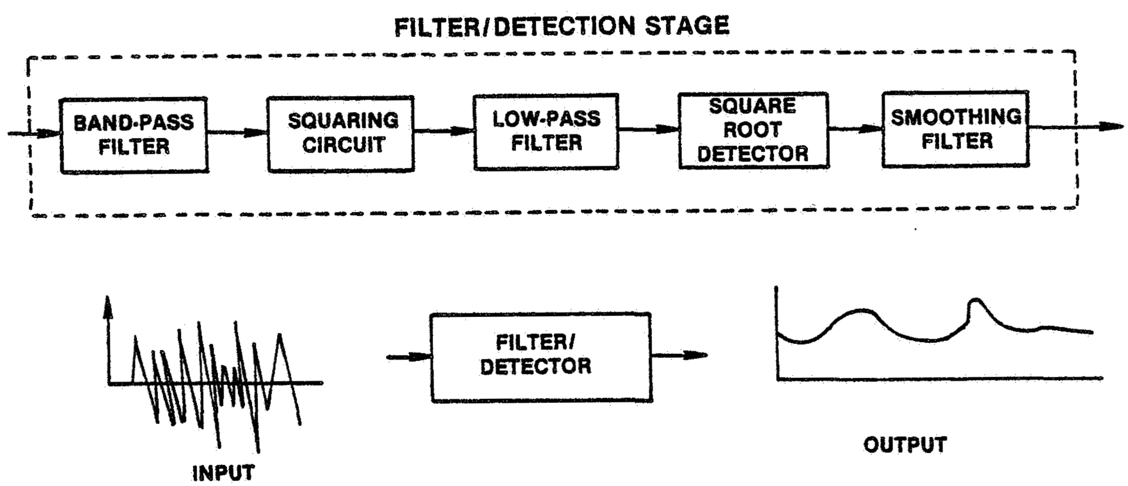


Figure 13. FASCOS Detection Stage and Transfer Characteristic

The controller periodically samples the state of the three comparator outputs and determines whether engine shut-down should be initiated based on a counting procedure. The voting protocol is quite simple. On a given sampling cycle a cut-off vote is registered only if all three controller inputs simultaneously indicate a redline exceedance. Shut-down is initiated only after three such consecutive cycles have been observed; otherwise the voting process is reinitialized. An effort to demonstrate this voting process is illustrated in Figure 15, which indicates a sequence of events leading to a cut-off decision.

The above qualitative description of the FASCOS system indicates a number of key issues to be addressed in system modeling, simulation and performance assessment, including

- Statistical characterization of the class of (random) functions representative of operational vibration signals.
- Modeling of the nonlinear detector output to representative stochastic inputs.
- Derivation of threshold exceedance persistence time probabilities representative of the comparator operation.
- Estimation of joint statistical properties required to model the probability of combined level exceedance as utilized in the controller voting process.

The above list is not exhaustive, but it does underline some significant technical considerations. At the outset, the (band-passed) vibration signals were considered representative of a random sine wave plus independent Gaussian noise process. This model admits a wide range of spectrum shapes and signal-to-noise level, and is yet mathematically tractable. Under this assumption a mathematical description of the filter/detection stage output (power spectrum and covariance function) was derived as a function of input, filter, and averaging characteristics. Limited computer results have demonstrated excellent agreement with empirical simulations performed by MSFC. The definition of threshold exceedance time persistance probabilities, to model the comparator output, represents a formidable theoretical problem. Several approximate formulations, however, have been implemented for evaluation. These are called the Rice method, the method of non-correlated pulses and the quadratic approximation method. (See "Non-Linear Transformations of Stochastic Processes,"

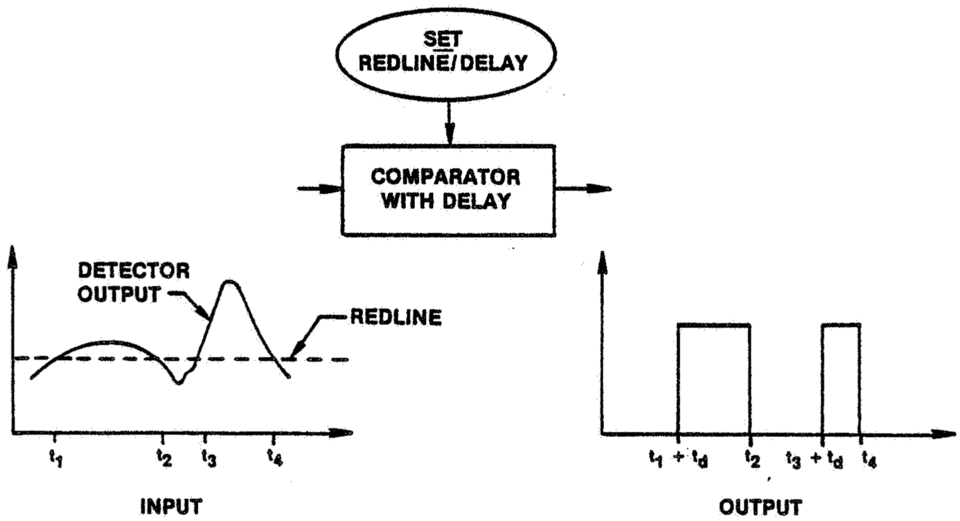


Figure 14. FASCOS Comparator Transfer Characteristics

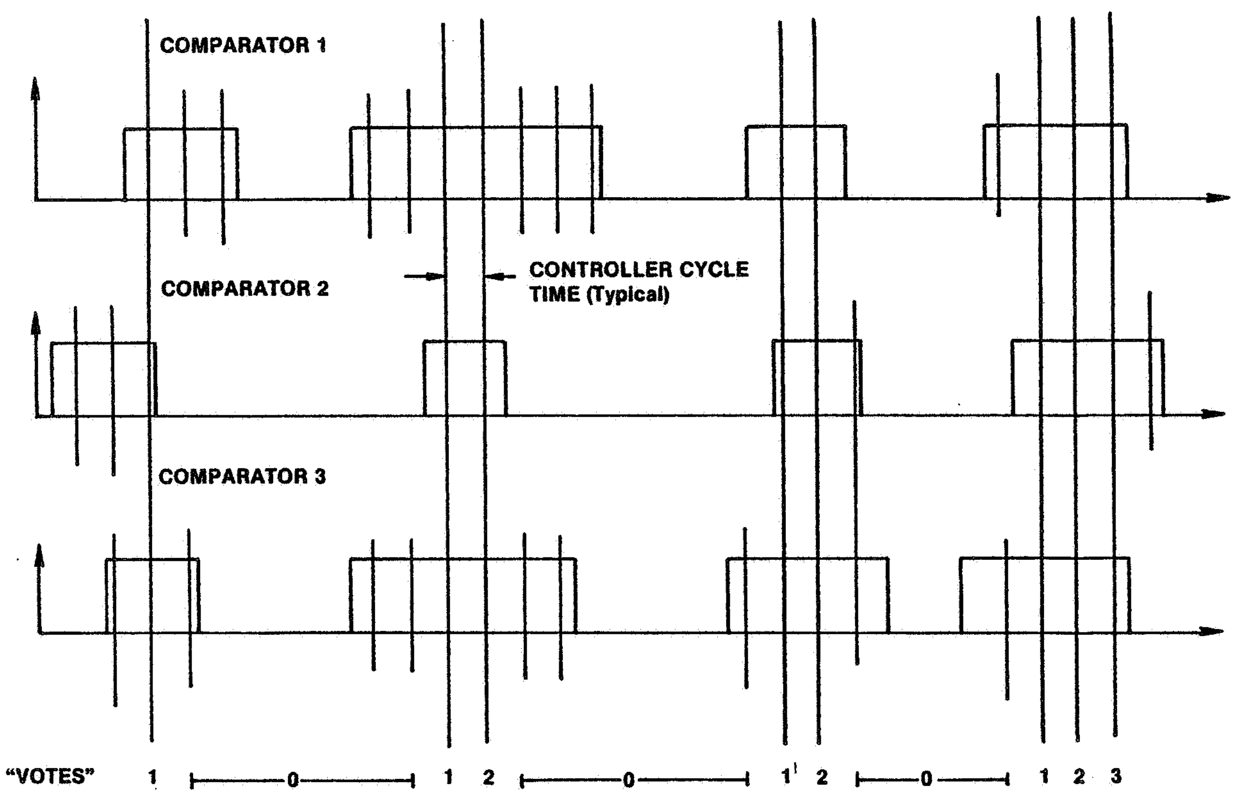


Figure 15. Illustration of FASCOS/Controller Voting Logic

by Tikhonov and Amiartov [RSIC No. QA273], for a comparison of these techniques and enabling assumptions.) Persistence time probability density estimates obtained by these approximations are illustrated in Figure 16, for an idealized white noise plus sine wave input. The curves represent the persistence time distribution of the detected mean-square above a three sigma threshold from the average output. Basic assumptions employed in all three approximations render them most valid for high threshold-to-mean values and short time periods. A theoretical extension of the Rice method was developed to relax these constraints. With regards to the final issue above, the estimation of joint properties between vibration signals appears best approached through empirical simulation. In the absence of such information, however, bounds on system behavior may be obtained by assuming joint properties (total statistical dependence/independence between monitored signals, for example).

By the above approach, a computer program was developed to define the probability of engine cut-off as a function of assigned redline values, turbopump vibration characteristics and FASCOS logic operation. Computer analyses were performed with the above model, based on vibration characteristics provided by MSFC, to estimate engine cut-off probabilities as a function of redline values. Finally, the program was installed on the MASSCOMP processor at the MSFC Systems Dynamics Laboratory. SDL personnel were provided computer program orientation at the conclusion of this task to permit FASCOS parameter evaluations by MSFC. A program listing of this analytical model is included at the end of this section.

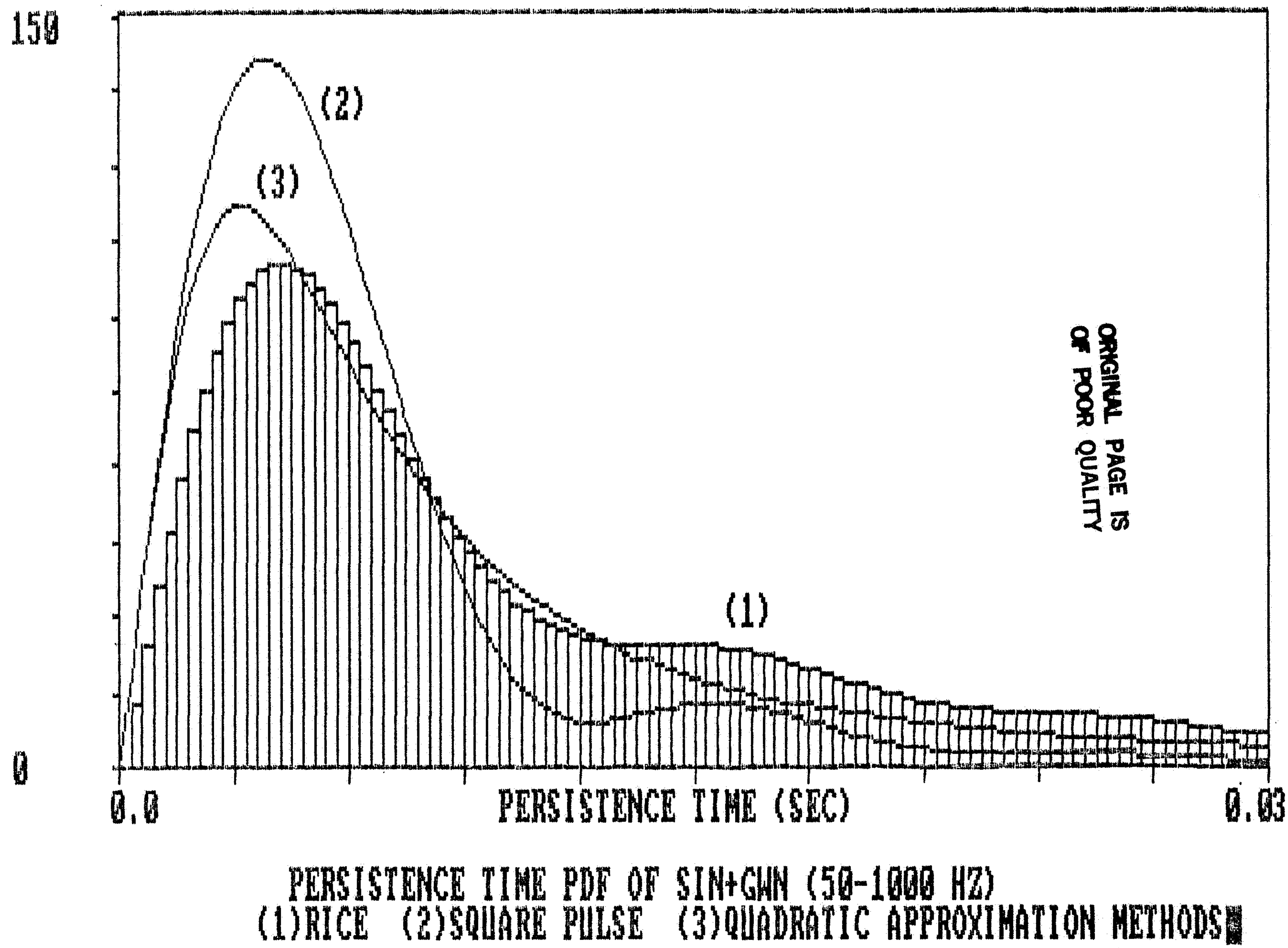


Figure 16. Three Approximations of the Persistence Time Distribution

2.4 Concluding Remarks

This report provides a cursory overview of study objectives and approaches applied by Wyle in the performance of Contract NAS8-33508. As a test/evaluation program, rigid, long term task planning was neither feasible nor desirable. On the contrary, most tasks performed under this contract were initiated on an ad hoc basis, motivated by observed or suspected SSME component failure modes. Continued coordination with the MSFC COTR was therefore maintained to revise task priorities based on SSME test results. Consistent with stringent SSME test schedules, evaluation results were immediately provided the COTR in the form of presentations and informal data packages. A detailed chronology of these evaluations is given in the technical progress reports provided under this contract. To illustrate the diversity of tasks accomplished under this contract, some topics recently investigated by Wyle in support of SSME dynamic evaluations are summarized in Table I at the end of this section. Several representative evaluations performed under this contract are described in the Appendices.

TABLE I. SOME TOPICS RECENTLY INVESTIGATED IN SUPPORT OF SSME DYNAMIC EVALUATIONS

- Pseudoharmonic Study. Performed nonlinear coherence analysis to indicate whether "apparent" harmonics were correlated with synchronous response.
- Pump configuration analysis. Applied linear discrimination analysis to pump measurements to assess statistical difference between design configurations.
- Trimodal density investigation. Performed analysis and simulations to determine time series characteristics yielding three mode probability densities observed in turbopump measurements.
- Source location investigation. Developed and applied analysis to estimate apparent source location based on geometry, wave speed and crosscorrelation measurements.
- FPB oxidizer, ASI line accelerometer and strain gauge evaluation.
- MMC inlet manifold elbow strain gauge analysis for strength calculations.
- Developed algorithm for computer data band program:
  - Computer selection of PSD time slices
  - Cumulative distribution
  - Amplitude indian belt format
- Analysis of internally instrumented pump:
- Transfer functions
  - Evaluation of ballpass frequencies
  - Calculation of contact angle from measured data
- Whirl study. This required compilation of a complete history of the pumps, by serial number, response characteristics, and time of occurrence.
- Rubbing model investigation. Statistical moments were derived for random sine wave plus noise processes with asymmetric clipping for comparison with observed turbopump measurements.
- STS-8. Investigation of ASI line malfunction required analysis of previous

test data to determine whether the phenomenon could be detected on the high pressure pumps during ground test firings.

- Calculation of ball train frequency for high-speed ball bearing. An attempt was made to modify frequency equations to include the effect of varying ball size within a single bearing.

- High synchronous study. Evaluated maximum/minimum amplitudes by pump and component serial number to define statistical changes in response levels.

- Developed relationships for data extrapolation as a function of engine power level.

- Cumulative distribution of HPOT. Fit data to normal, Rayleigh and gamma distributions. Gamma was found to be best fit to empirical observations.

- Modulation investigation. The thrust was to determine the time functions that produce certain side-band frequencies which often appear in the data and are usually considered noise. A next step would be to evaluate the physical functions that produce such time histories.

Results of the above investigations have been provided MSFC through technical progress reports, informal data packages and presentations.

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FASCOS PROGRAM LISTING

D Line# 1 7 Microsoft FORTRAN77 V3.20 02/84

```
C      LINK FASCOS+FFTSUB+FFT842
C      OUTPUT PSD IS ODE-SIDE PSD OF X5
       DIMENSION BBWW(2)
       CHARACTER*16 FPSD5,FCOR5,F1TO5
       COMMON WTR(4096),WTI(4096),XR(4096),XI(4096),S(4100)
       INTEGER TTI,TTO
       DOUBLE PRECISION NF2,NF3,NF4
       WRITE(*,'(A)')' ENTER  VARIANCE OF X1(T) AFTER BANDPASS FILTER'
       READ(*,*)VVV
C      WRITE(*,'(A)')' ENTER 1 FOR RC AVERAGE FILTER'
C      READ(*,*)IFRC
C      WRITE(*,'(A)')' ENTER 1 FOR ANALOG RC FILTER; 2 FOR DIGITAL RC'
C      READ(*,*)IFAD
       IFAD=2
       IF(IFAD.NE.1)THEN
       WRITE(*,'(A)')' ENTER MAX FREQ (HZ) ( ENTER SAMPLING FREQ )'
       READ(*,*)FS
       ENDIF
       WRITE(*,'(A)')' ENTER # OF DATA IN OUTPUT PSD NN ( LE 4096)'
       WRITE(*,'(A)')' NOTE: THIS IS UPTO FS (SAMPLING FREQ)'
       WRITE(*,'(A)')'       OUTPUT PSD OF X5 HAS NN/2 DATA UPTO FS/2'
       READ(*,*)NN
       WRITE(*,'(A)')' ENTER FREQUENCY OF SIN WAVE'
       READ(*,*)FSIN
       WRITE(*,'(A)')' ENTER FREQ F1 & F2 OF FASCOS FILTER'
       READ(*,*)F1,F2
       WRITE(*,'(A)')' ENTER AVERAGE TIME IN SEC( =2*RC)'
       READ(*,*)T
       WRITE(*,'(A)')' ENTER SIGNAL TO NOISE RATIO (NASA DEFINITION)'
       READ(*,*)ET
       ET=ET*ET/(1-ET*ET)
       WRITE(*,'(A)')' ENTER  CUTOFF FREQ IN POST-RIPPLE FILTER'
       READ(*,*)FC
       WRITE(*,'(A)')' ENTER  ORDER OF BUTTERWORTH FILTER'
       READ(*,*)NORDER
       WRITE(*,'(A)')' ENTER  1 FO ANALOG; 2 FOR DIGITAL BUTTERWORTH'
       READ(*,*)IFBW
       WRITE(*,'(A)')' ENTER MAX TIME LAG OF OUTPUT R(T) IN SEC'
       READ(*,*)TMAX
       WRITE(*,'(A)')' ENTER # OF DATA OF OUTPUT R(T) NOUT'
       WRITE(*,'(A)')' NOTE: NN/2+NOUT MUST LE. 4096'
       READ(*,*)NOUT
       WRITE(*,'(A)')' ENTER OUTPUT FILNAM OF PSD OF X5'
       READ(*,'(A)')FPSD5
       WRITE(*,'(A)')' ENTER OUTPUT FILNAM OF R(T), R"(T) & R`(T)'
       READ(*,'(A)')FCOR5
       WRITE(*,'(A)')' ENTER OUTPUT FILNAM AVE & DEV OF X1 TO X5'
       READ(*,'(A)')F1TO5
       WRITE(*,'(A)')' ENTER 1 FOR SETTING S(0)=0.'
       READ(*,*)IFS0
       OPEN(2,FILE=FPSD5,STATUS='NEW')
       OPEN(6,FILE=F1TO5,STATUS='NEW')
C      *********************************
       PI=3.141592653
       NIN=NN/2
       IFRC=1
       FMAX=FS/2.
       DT=1/FS
       RC=T/2.
```

```
          ARC=EXP(-DT/RC)
          A1RC=(1-ARC)**2
          A2RC=1+ARC*ARC
          C2=2*PI*DT
          C1=2*PI*RC
          BW=F2-F1
          DF=FS/(NN-1)
          NNMAX=2*F2/DF
          FF1=2*F1
          FF2=BW
          FF3=BW+FF1
          FF4=FF3+FF2
          NF1=(FF1/DF)+1
          NF2=FF2/DF+1
          NF3=FF3/DF+1
          NF4=FF4/DF+1
          A=VVV*0.5/(BW*(1+ET))
          VAR1=2*BW*A
          A2=A*A
          T2A2=2*A2
          T4A2=4*A2
          S1=-1*T4A2
          S2=S1/2.
          S3=-S2
          S4=S2
          B1=T4A2*BW
          B2=T4A2*(BW-2*F1)
          B3=B2/2.
          B4=B1/2.
          NL2=NF2
          NL3=NF3
          NL4=NF4
     C    ***********************************
          IF(NF1.GT.NN)NF1=NN
          DO 11 I=1,NF1
1         IF(I.GE.NN+1)GOTO 20
1         S(I)=B1+S1*(I-1)*DF
1    11   CONTINUE
          IF(NF2.GT.10000) GOTO 20
          NL2=NF2
          DO 12 I=NF1+1,NL2
1         IF(I.GE.NN+1)GOTO 20
1         S(I)=B2+S2*((I-1)*DF-2*F1)
1    12   CONTINUE
          IF(NF3.GT.10000) GOTO 20
          NL3=NF3
          DO 13 I=NL2+1,NL3
1         IF(I.GE.NN+1)GOTO 20
1         S(I)=B3+S3*((I-1)*DF-BW)
1    13   CONTINUE
          IF(NF4.GT.10000) GOTO 20
          NL4=NF4
          DO 14 I=NL3+1,NL4
1         IF(I.GE.NN+1)GOTO 20
1         S(I)=B4+S4*((I-1)*DF-BW-2*F1)
1    14   CONTINUE
          DO 15 I=NL4+1,NN
1         IF(I.GE.NN+1)GOTO 20
1         S(I)=0.
```

```
D Line# 1       7
1       15      CONTINUE
        20      CONTINUE
                DO 21 I=1,NN
1                IF(I.GT.NL4)GOTO 21
1                W=(I-1.)*DF
1                IF(W.LT.(F2-FSIN))THEN
1                S(I)=S(I)+8*BW*ET*A2
1                ELSE
1               IF(W.LT.(FSIN-F1).OR.(W.GT.(F1+FSIN).AND.W.LT.(F2+FSIN)))THEN
1                 S(I)=S(I)+4*BW*ET*A2
1                 ELSE
1                 S(I)=S(I)
1                 ENDIF
1                ENDIF
1       21      CONTINUE
                NC=2*FSIN/DF+1
                S(NC)=(A*BW*ET)**2+S(NC)
        C       WRITE(1,*)(S(I),I=1,NN)
                VRV=S(1)
                IF(IFSO.EQ.1)VRV=0.
                DO 478 I=2,NN
1               VRV=VRV+S(I)
1       478     CONTINUE
                VRV=VRV*2*DF
                 SMO=S(1)
                 IF(IFSO.EQ.1)SMO=0.
                 F=0
                IF(IFRC.EQ.1)THEN
                 DO 222 I=2,NN
1                F=F+DF
1                  IF(IFAD.NE.1)THEN
1                   S(I)=S(I)*A1RC/(A2RC-2*ARC*COS(C2*F))
1                  ELSE
1                   S(I)=S(I)/(1+(C1*F)**2)
1                  ENDIF
1       222      SMO=SMO+S(I)
                ELSE
                 DO 22 I=2,NN
1                F=F+DF
1                Q=PI*T*F
1                S(I)=S(I)*((SIN(Q)/Q)**2)
1                SMO=SMO+S(I)
1       22       CONTINUE
                ENDIF
                SMO=SMO*2*DF
                AAA=2*A*BW*(1+ET)
                AA4=SQRT(0.5*SQRT(4*AAA*AAA-2*SMO))
                SM4=AAA-AA4*AA4
                DEV1=SQRT(VVV)
                WRITE(*,121)ZO,VVV,DEV1
                DEV2=SQRT(VRV)
                WRITE(*,122)VVV,VRV,DEV2
                DEV3=SQRT(SMO)
                WRITE(*,123)AAA,SMO,DEV3
                DEV4=SQRT(SM4)
                WRITE(*,124)AA4,SM4,DEV4
                WRITE(6,*)ZO,DEV1
                WRITE(6,*)VVV,DEV2
                WRITE(6,*)AAA,DEV3
```

```
          WRITE(6,*)AA4,DEV4
    121   FORMAT(' AVE1= ',E16.8,' VAR1= ',E16.8,' DEV1= ',E16.8)
    122   FORMAT(' AVE2= ',E16.8,' VAR2= ',E16.8,' DEV2= ',E16.8)
    123   FORMAT(' AVE3= ',E16.8,' VAR3= ',E16.8,' DEV3= ',E16.8)
    124   FORMAT(' AVE4= ',E16.8,' VAR4= ',E16.8,' DEV4= ',E16.8)
    126   FORMAT(' AVE5= ',E16.8,' VAR5= ',E16.8,' DEV5= ',E16.8)
          NFFT=NN
          A4=AA4
          NNP2=NFFT+2
          NNP22=NNP2/2
          A4S=A4*A4
          A4F=A4S*A4S
          PI2=2*PI
          TIME=NFFT/FS
          DF=FS/NFFT
          DT=1/FS
          DT2=DT*2
          DF2=DF*2
          IF(IFSO.EQ.1)S(1)=0.
          CALL FFT(S,NNP2,1)
          DO 601 I=1,NNP22
1   601   S(I)=S(2*I-1)*NFFT
          DO 602 I=1,NNP22-2
1   602   S(NNP22+I)=S(NNP22-I)
          S(NFFT+1)=0.
          S(NFFT+2)=0.
          DO 3 I=1,NFFT
1         S(I)=DF2*S(I)
1   3     CONTINUE
    C     ******** CALCULATE R4(T) FROM R3(T) *********
          R30=S(1)
          DO 66 I=1,NFFT
1         S(I)=-A4S+0.5*SQRT(4*A4F+2*S(I))
1   66    CONTINUE
          R40=S(1)
    125   FORMAT(' R3(0)= 'E16.8,' R4(0)= ',E16.8)
          CALL FFT(S,NNP2,1)
          DO 606 I=1,NNP22
1   606   S(I)=S(2*I-1)*NFFT
          DO 607 I=1,NNP22-2
1   607   S(NNP22+I)=S(NNP22-I)
          DO 4 I=1,NNMAX
1   4     S(I)=S(I)*DT2
          S(1)=S(1)/2.
          DO 224 I=NNMAX+1,NFFT
1   224   S(I)=0.
    C     WRITE(11,*)(S(I),I=1,NFFT/2)   ****** PSD OF X4 **********
          CALL POSTR(S,NFFT/2,FC,NORDER,DF,VAR5,FS,IFBW)
          DEV5=SQRT(VAR5)
          WRITE(*,126)AA4,VAR5,DEV5
          WRITE(6,*)AA4,DEV5
          WRITE(2,*)(S(I),I=1,NIN)
    C**********************
          FSEQ=1.0
          SIGO=1
          SIGO=FSEQ*ALOG(SIGO)
          DLTSIG=1
          DLTSIG=FSEQ*ALOG(DLTSIG)
          OMEO=0.
```

```
      DLTOMG=FMAX*TMAX/(NIN*NOUT)
      DF=FMAX/(NIN-1)
      DT=TMAX/NOUT
      DF2=DF*2
      PI=4.0*ATAN(1.0)
      PI2=PI*2.
      DFPI2=DF*PI2
C***********************************
C     WRITE(*,'(A)')'  ENTER STARTING FREQ IN HZ'
C     READ(*,*)OMEO
C     WRITE(*,'(A)')'  ENTER ENDING FREQ IN HZ'
C     READ(*,*)FEND
C     DLTOMG=(FEND-OMEO)/(NOUT-1.)
       OPEN(12,FILE=FCOR5,STATUS='NEW')
C***************************************
      NFFT=NIN+NOUT
      DO 30 I=1,12
      NTEST=2**I
      IF(NTEST.GE.NFFT)GOTO 40
   30 CONTINUE
      WRITE(*,'(A)')'  N TOO BIG FOR FFT'
      STOP
   40 NFFT=NTEST
C***************************************
       IF(IFSO.EQ.1)S(1)=0.
        DO 82 IL=1,NIN
      S(IL)=S(IL)/2.
      XR(IL)=S(IL)
   82 CONTINUE
C     WRITE(*,'(A)')' BEFORE R(T)'
C*************************** R(T) ******************************
      CALL ZERO(XI,NFFT)
      CALL CZT(XR,XI,NIN,NOUT,DLTSIG,DLTOMG,WTR,WTI,SIGO,OMEO,
     1  O,NFFT,FSEQ)
C     WRITE(*,'(A)')' FINISH R(T)'
      DO 51 I=1,NOUT
   51 XR(I)=XR(I)*DF2
      EEE=XR(NOUT)*1.02
      DO 301 I=1,NOUT
      IF(XR(I).LE.EEE)GOTO 302
  301 CONTINUE
  302 K=0
      BBB=10./(NOUT-I)
      DO 303 J=I,NOUT
      K=K+1
      XR(J)=XR(J)*EXP(-BBB*K)
  303 CONTINUE
      WRITE(12,*)(DBLE(XR(I)),I=1,NOUT)
C*************************** R"(T) ******************************
      FF=-DFPI2
      DO 502 I=1,NIN
      FF=FF+DFPI2
  502 XR(I)=S(I)*FF*FF
      DO 5022 I=NIN+1,NFFT
 5022 XR(I)=0.
      CALL ZERO(XI,NFFT)
      CALL CZT(XR,XI,NIN,NOUT,DLTSIG,DLTOMG,WTR,WTI,SIGO,OMEO,
     1  O,NFFT,FSEQ)
      DO 52 I=1,NOUT
```

```
D Line# 1     7                                          Microsoft FORTRAN77 V3.20 02/84
1       52    XR(I)=-DF2*XR(I)
              WRITE(12,*)(DBLE(XR(I)),I=1,NOUT)
              RTTO=-XR(1)
              WRITE(*,127)RTTO
              WRITE(6,*)RTTO
        127   FORMAT(' VARIANCE OF SLOPE OF RMS TIME SERIES=-R"(0) = ',E16.8)
              WRITE(*,'(A)')' N* = EXPECT # OF UPCROSSING OF R IN TIME T'
              WRITE(*,'(A)')' TBAR= EXPECT PERSISTENCE TIME OF REDLINE R'
              UP=SQRT(RTTO)/(PI2*DEV5)
              UPI=1./UP
              WRITE(*,128)UP
              WRITE(*,129)UPI
        128   FORMAT(' N* = ',F15.8,' * T * EXP(-0.5*R**2)')
        129   FORMAT(' TBAR = ',F15.8,' * EXP(0.5*R**2) * ERR(R)')
              WRITE(*,'(A)')' ERR(R)= Pr( X GREATER THEN R ) X IS UNIT NORMAL'
        C     WRITE(*,'(A)')' FINISH R"(T)'
        C************************** R'(T) ********************************
              FF=-DFPI2
              DO 503 I=1,NIN
1             FF=FF+DFPI2
1       503   XR(I)=S(I)*FF
              DO 5033 I=NIN+1,NFFT
1       5033  XR(I)=0.
              CALL ZERO(XI,NFFT)
              CALL CZT(XR,XI,NIN,NOUT,DLTSIG,DLTOMG,WTR,WTI,SIGO,OMEO,
             1  O,NFFT,FSEQ)
              DO 53 I=1,NOUT
1       53    XR(I)=DF2*XI(I)
              WRITE(12,*)(DBLE(XR(I)),I=1,NOUT)
        C     WRITE(*,'(A)')' FINISH R`(T)'
        C************************ R""(O) ********************************
              R40=0.
              FF=-DFPI2
              DO 504 I=1,NIN
1             FF=FF+DFPI2
1             XR(I)=S(I)*FF**4
1       504   R40=R40+XR(I)
              R40=R40*DF2
              WRITE(12,*)DBLE(R40)
        C*****************************************************
              CLOSE(2)
              STOP
              END
```

Name	Type	Offset	P	Class
A	REAL	218		
A1RC	REAL	146		
A2	REAL	226		
A2RC	REAL	150		
A4	REAL	636		
A4F	REAL	652		
A4S	REAL	648		
AA4	REAL	350		
AAA	REAL	346		
ALOG				INTRINSIC
ARC	REAL	142		
ATAN				INTRINSIC
B1	REAL	254		

```
C     PROGRAM PSTAR.FOR----- 3 STEP MEMORY MARKOV MODELLING OF P.T.
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 A0(50),A1(50),V0(300),PV0(300),PSTAR(20),QSTAR(20)
      REAL*8 SM(3,3),TM(3),RM(3),SMI(3,3),TP(3),REDV(10)
      DIMENSION L3(3),M3(3)
      REAL*8 MU(20),DEL(20,20),ERR(1005)
      CHARACTER*16 F1,F2,FRED,FOUT
      COMMON PI2,ERR
      KK=3
      WRITE(*,'(A)')' ENTER # OF REDLIN'
      READ(*,*)NRED
      IF(NRED.EQ.1)THEN
      WRITE(*,'(A)')' ENTER REDLINE ( ? DEV )'
      READ(*,*)REDV(1)
      ELSE
      WRITE(*,'(A)')' ENTER FILNAM OF REDLIN'
      READ(*,'(A)')FRED
      OPEN(11,FILE=FRED,STATUS='OLD')
      READ(11,*)(REDV(I),I=1,NRED)
      CLOSE(11)
      ENDIF
      WRITE(*,'(A)')' ENTER INPUT R(T),R`(T) FILNAM'
      READ(*,'(A)')F1
      WRITE(*,'(A)')' ENTER OUTPUT INFOMATION FILNAM '
      READ(*,'(A)')F2
      WRITE(*,'(A)')' ENTER OUTPUT FILNAM OF PSTAR'
      READ(*,'(A)')FOUT
      WRITE(*,'(A)')' ENTER ORDER OF RICE THEORY=NN (NOT INCLUDE X0)'
      READ(*,*)NN
      WRITE(*,'(A)')' ENTER # OF DATA IN ERROR FUNCTION'
      READ(*,*)NERR
      WRITE(*,'(A)')' ENTER # OF V0'
      READ(*,*)NV0
      WRITE(*,'(A)')' ENTER MAX VALUE OF V0  ( ? DEV(V0) )'
      READ(*,*)V0MAX
      WRITE(*,'(A)')' ENTER # OF X'
      READ(*,*)NX
      NX2=NX*2
      WRITE(*,'(A)')' ENTER MAX VALUE OF X ( ? DEV(X) )'
      READ(*,*)XMAX
      WRITE(*,'(A)')' ENTER 1 FOR PRINTING INNER LOOP PARAMETERS'
      READ(*,*)INNER
      CALL SERR(ERR,NERR)
      OPEN(6,FILE=F2,STATUS='NEW')
      WRITE(6,'(A)')' PROGRAM JEN3'
      WRITE(6,501)KK
      WRITE(6,502)NERR
      WRITE(6,503)NN
      WRITE(6,504)NV0
      WRITE(6,505)V0MAX
      WRITE(6,506)NX
      WRITE(6,507)XMAX
  501 FORMAT(' MEMORY STEP = ',I2)
  502 FORMAT(' # OF DATA IN ERROR FUNCTION = ',I6)
  503 FORMAT(' ORDER OF RICE THEORY = ',I3)
  504 FORMAT(' # OF INITIAL SLOPE V0 = ',I5)
  505 FORMAT(' MAX VALUE OF V0 = ',F8.4,'  DEV(V0)')
  506 FORMAT(' # OF X = ',I4)
  507 FORMAT(' MAX VALUE OF X  = ',F8.4,'  DEV(X)')
```

```
D Line# 1      7                                   Microsoft FORTRAN77 V3.20 02/84
               OPEN(1,FILE=F1,STATUS='OLD')
               OPEN(2,FILE=FOUT,STATUS='NEW')
               READ(1,*)(A0(I),I=0,NN)
               READ(1,*)(A1(I),I=0,NN)
               VARV=A1(0)
                PI=4.D0*DATAN(1.D0)
                PI2=PI*2
                DVO=VOMAX*DSQRT(VARV)/NVO
                AREA=0.
                DO 1 I=1,NVO
1               VO(I)=I*DVO
1               PVO(I)=DEXP(-0.5*VO(I)*VO(I)/VARV)*VO(I)
1               AREA=AREA+PVO(I)
1         1     CONTINUE
                DO 2 I=1,NVO
1         2     PVO(I)=PVO(I)/AREA
                WRITE(*,*)(PVO(I),I=1,NVO)
               DO 3 I=1,NN
1              DO 3 J=1,NN
2              DEL(I,J)=A0(IABS(I-J))-A0(I)*A0(J)-A1(I)*A1(J)/VARV
2         3    CONTINUE
          C
               DO 1000 NOPQ=1,NRED
1              CALL DZERO(PSTAR,NN)
1              CALL DZERO(QSTAR,NN)
1              RED=REDV(NOPQ)
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              IF(INNER.EQ.1)THEN
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              WRITE(6,*)'    '
1              ENDIF
1              WRITE(6,606)RED
1              WRITE(*,606)RED
1         606  FORMAT(1X,'****************** REDLINE=',F8.4,' **************')
1         C*********************************************************************
1              DO 9999 MM=KK+1,NN
2              WRITE(*,'(A)')' *******************************************'
2              IF(INNER.EQ.1)WRITE(6,'(A)')' *********************************'
2               BM=DEL(MM,MM)
2               DO 9991 I=1,KK
3               TM(I)=DEL(MM,MM-I)
3               DO 9991 J=1,KK
4         9991  SM(I,J)=DEL(MM-I,MM-J)
2               CALL EQUAL3(SM,SMI,KK)
2               CALL DMINV(SMI,KK,DTM,L3,M3)
2               CALL DGMPRD(TM,SMI,TP,1,KK,KK)
2               VZM=BM-TP(1)*TM(1)-TP(2)*TM(2)-TP(3)*TM(3)
2               DZM=DSQRT(VZM)
2               DEVX1=DSQRT(SM(1,1))
2               DEVX2=DSQRT(SM(2,2))
2               DEVX3=DSQRT(SM(3,3))
2               COR12=SM(1,2)/(DEVX1*DEVX2)
2               COR13=SM(1,3)/(DEVX1*DEVX3)
2               COR23=SM(2,3)/(DEVX2*DEVX3)
```

```
D Line# 1       7                          Microsoft FORTRAN77 V3.20 02/84
2                CORR=1-COR*COR
2               DX1=XMAX*DEVX1/NX
2               DX2=XMAX*DEVX2/NX
2               DX3=XMAX*DEVX3/NX
2               QO=DX1*DX2*DX3/(PI2**1.5*DSQRT(DABS(DTM)))
2               IF(INNER.EQ.1)WRITE(6,601)DZM,DEVX1,DEVX2,DEVX3,COR12,COR23,
2              1 COR13
2               WRITE(*,601)DZM,DEVX1,DEVX2,DEVX3,COR12,COR23,COR13
2         601   FORMAT(1X,7(E9.4,1X))
2               WRITE(*,'(A)')' BEFORE 999'
2                DO 999 II=1,NVO
3                 DO 991 I=1,NN
4         991     MU(I)=RED*AO(I)-VO(II)*A1(I)/VARV
3                 AM=MU(MM)
3                 DO 992 I=1,KK
4         992     RM(I)=MU(MM-I)
3                XMIN1=RM(1)-XMAX*DEVX1
3                XMIN2=RM(2)-XMAX*DEVX2
3                XMIN3=RM(3)-XMAX*DEVX3
3                XMAX1=RM(1)+XMAX*DEVX1
3                XMAX2=RM(2)+XMAX*DEVX2
3                XMAX3=RM(3)+XMAX*DEVX3
3                S1=DMAX1(RED,XMIN1)
3                S2=DMAX1(RED,XMIN2)
3                S3=DMAX1(RED,XMIN3)
3                NS1=(S1-XMIN1)/DX1
3                NS2=(S2-XMIN2)/DX2
3                NS3=(S3-XMIN3)/DX3
3                X1=S1-DX1
3                PS=0.DO
3                QS=0.DO
3                IF(S1.GT.XMAX1)GOTO 100
3               DO 99 JJ=NS1,NX2
4                X1=X1+DX1
4                Q1=(X1-RM(1))
4                H1=Q1*Q1*SMI(1,1)
4                WK2=2*Q1*SMI(1,2)
4                WK3=Q1*SMI(1,3)
4                AZM1=AM+TP(1)*Q1
4                IF(S2.GT.XMAX2)GOTO 99
4                X2=S2-DX2
4               DO 9 LL=NS2,NX2
5                X2=X2+DX2
5                Q2=X2-RM(2)
5                H2=H1+Q2*(Q2*SMI(2,2)+WK2)
5                WK1=2*(WK3+Q2*SMI(2,3))
5                AZM2=AZM1+TP(2)*Q2
5                IF(S3.GT.XMAX2)GOTO 9
5                X3=S3-DX3
5               DO 22 IJK=NS3,NX2
6                X3=X3+DX3
6                Q3=X3-RM(3)
6                H3=H2+(WK1+Q3*SMI(3,3))*Q3
6                AZM=AZM2+TP(3)*Q3
6                GGG=GG1((RED-AZM)/DZM,NERR)
6                QQ=DEXP(-H3/2.DO)
6                PS=PS+QQ*GGG
6                QS=QS+QQ
6         22    CONTINUE
```

```
D Line# 1      7                                      Microsoft FORTRAN77 V3.20 02/84
5     9       CONTINUE
4     99      CONTINUE
3     100     PS=PS*Q0*PVO(II)
3             QS=QS*Q0*PVO(II)
3             PSTAR(MM)=PSTAR(MM)+PS
3             QSTAR(MM)=QSTAR(MM)+QS
3             IF(INNER.EQ.1)WRITE(6,602)II,PVO(II),PS,QS,NS1,NS2,NS3,
3            1 (RM(I),I=1,KK)
3             WRITE(*,602)II,PVO(II),PS,QS,NS1,NS2,NS3,(RM(I),I=1,KK)
3     602     FORMAT(1X,I4,3(1X,E8.3),3I4,3(1X,E8.3))
3     999     CONTINUE
2               PQ=PSTAR(MM)/QSTAR(MM)
2               IF(MM.EQ.KK+1)THEN
2               PP1=PSTAR(MM)
2               ELSE
2               PP1=PP1*PQ
2               ENDIF
2             IF(INNER.EQ.1)THEN
2             WRITE(6,'(A)')'**** MM **** P* **** Q* **** P*/Q* **** PP ****'
2             ENDIF
2             WRITE(6,603)MM,PSTAR(MM),QSTAR(MM),PQ,PP1
2             WRITE(*,'(A)')'**** MM **** P* **** Q* **** P*/Q* **** PP ****'
2             WRITE(*,603)MM,PSTAR(MM),QSTAR(MM),PQ,PP1
2     603     FORMAT(1X,I5,4E16.8)
2     9999    CONTINUE
1     C       WRITE(2,*)(PSTAR(I),I=1,NN)
1     C       WRITE(2,*)(QSTAR(I),I=1,NN)
1             W1=PSTAR(KK+1)
1             W2=1.
1             DO 1001 I=KK+2,NN
2             W1=W1*PSTAR(I)
2     1001    W2=W2*QSTAR(I)
1             IF(W2.NE.0.D0)PP=W1/W2
1     C       WRITE(2,*)PP
1             WRITE(6,'(A)')' FILNAL PROBABILITY IS:'
1             WRITE(6,*)W1,W2,PP
1             WRITE(*,'(A)')' FILNAL PROBABILITY IS:'
1             WRITE(*,*)W1,W2,PP
1             WRITE(2,*)PP
1     1000    CONTINUE
              STOP
              END
```

Name	Type	Offset	P	Class
A0	REAL*8	2		
A1	REAL*8	402		
AM	REAL*8	10248		
AREA	REAL*8	9972		
AZM	REAL*8	10496		
AZM1	REAL*8	10408		
AZM2	REAL*8	10456		
BM	REAL*8	10084		
COR	REAL*8	10180		
COR12	REAL*8	10148		
COR13	REAL*8	10156		
COR23	REAL*8	10164		
CORR	REAL*8	10172		
DABS				INTRINSIC

DATAN			INTRINSIC
DEL	REAL*8	6402	
DEVX1	REAL*8	10124	
DEVX2	REAL*8	10132	
DEVX3	REAL*8	10140	
DEXP			INTRINSIC
DMAX1			INTRINSIC
DSQRT			INTRINSIC
DTM	REAL*8	10100	
DVO	REAL*8	9964	
DX1	REAL*8	10188	
DX2	REAL*8	10196	
DX3	REAL*8	10204	
DZM	REAL*8	10116	
ERR	REAL*8	8	/COMMQQ/
F1	CHAR*16	9634	
F2	CHAR*16	9650	
FOUT	CHAR*16	9666	
FRED	CHAR*16	9610	
GGG	REAL*8	10504	
H1	REAL*8	10384	
H2	REAL*8	10440	
H3	REAL*8	10488	
I	INTEGER*4	9626	
IABS			INTRINSIC
II	INTEGER*4	10236	
IJK	INTEGER*4	10472	
INNER	INTEGER*4	9718	
J	INTEGER*4	9992	
JJ	INTEGER*4	10368	
KK	INTEGER*4	9602	
L3	INTEGER*4	6218	
LL	INTEGER*4	10424	
M3	INTEGER*4	6230	
MM	INTEGER*4	10076	
MU	REAL*8	6242	
NERR	INTEGER*4	9686	
NN	INTEGER*4	9682	
NOPQ	INTEGER*4	10000	
NRED	INTEGER*4	9606	
NS1	INTEGER*4	10332	
NS2	INTEGER*4	10336	
NS3	INTEGER*4	10340	
NVO	INTEGER*4	9690	
NX	INTEGER*4	9702	
NX2	INTEGER*4	9706	
PI	REAL*8	9956	
PI2	REAL*8	0	/COMMQQ/
PP	REAL*8	10614	
PP1	REAL*8	10570	
PQ	REAL*8	10562	
PS	REAL*8	10352	
PSTAR	REAL*8	6058	
PVO	REAL*8	3202	
Q0	REAL*8	10212	
Q1	REAL*8	10376	
Q2	REAL*8	10432	
Q3	REAL*8	10480	
QQ	REAL*8	10520	

```
QS       REAL*8          10360
QSTAR    REAL*8           5602
RED      REAL*8          10008
REDV     REAL*8           5978
RM       REAL*8           5954
S1       REAL*8          10308
S2       REAL*8          10316
S3       REAL*8          10324
SM       REAL*8           5762
SMI      REAL*8           5882
TM       REAL*8           5834
TP       REAL*8           5858
VO       REAL*8            802
VOMAX    REAL*8           9694
VARV     REAL*8           9948
VZM      REAL*8          10108
W1       REAL*8          10594
W2       REAL*8          10602
WK1      REAL*8          10448
WK2      REAL*8          10392
WK3      REAL*8          10400
X1       REAL*8          10344
X2       REAL*8          10416
X3       REAL*8          10464
XMAX     REAL*8           9710
XMAX1    REAL*8          10284
XMAX2    REAL*8          10292
XMAX3    REAL*8          10300
XMIN1    REAL*8          10260
XMIN2    REAL*8          10268
XMIN3    REAL*8          10276
```

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```
                SUBROUTINE EQUAL3(A,B,N)
                REAL*8 A(3,3),B(3,3)
                DO 1 I=1,N
1               DO 1 J=1,N
2         1     B(I,J)=A(I,J)
                RETURN
                END

Name     Type          Offset P Class

A        REAL*8             0 *
B        REAL*8             4 *
I        INTEGER*4      10622
J        INTEGER*4      10630
N        INTEGER*4          8 *


                SUBROUTINE SERR(ERR,NERR)
          C     AREA UNDER Nx(0,1) FROM X=0 TO R
                REAL*8 ERR(1),PI,C1,T,TP1,TP2,DT
                PI=4.D0*DATAN(1.D0)
                C1=DSQRT(2.D0*PI)
                DT=5.D0/NERR
                DT2=DT/2.
                T=0.D0
                DO 1 I=1,NERR
```

```
D Line# 1      7
1              T=T+DT
1          1   ERR(I)=DEXP(-0.5*T*T)/C1
               TP1=ERR(1)
               ERR(1)=(ERR(1)+1/C1)*DT*0.5
               DO 2 I=2,NERR
1              TP2=ERR(I)
1              ERR(I)=ERR(I-1)+DT2*(TP1+ERR(I))
1              TP1=TP2
1          2   CONTINUE
               ERR(0)=0.D0
               RETURN
               END
```

Name	Type	Offset	P	Class
C1	REAL*8	10646		
DATAN				INTRINSIC
DEXP				INTRINSIC
DSQRT				INTRINSIC
DT	REAL*8	10654		
DT2	REAL	10662		
ERR	REAL*8	0	*	
I	INTEGER*4	10674		
NERR	INTEGER*4	4	*	
PI	REAL*8	10638		
T	REAL*8	10666		
TP1	REAL*8	10682		
TP2	REAL*8	10694		

```
               DOUBLE PRECISION FUNCTION GG1(XX,NERR)
           C     CALCULATE AREA FROM XX TO INFINITE OF Nx(0,1)
               IMPLICIT REAL*8 (A-H,O-Z)
               COMMON PI2,ERR
               REAL*8 ERR(1)
               X=DABS(XX)
               NN=X*NERR/5.D0
               IF(NN.GE.NERR)THEN
               GG1=0.5
               GOTO 9
               ENDIF
               GG1=ERR(NN)
           9   CONTINUE
               IF(XX.GT.0.D0)THEN
               GG1=0.5-GG1
               ELSE
               GG1=0.5+GG1
               ENDIF
               RETURN
               END
```

Name	Type	Offset	P	Class
DABS				INTRINSIC
ERR	REAL*8	8		/COMMQQ/
NERR	INTEGER*4	4	*	
NN	INTEGER*4	10710		
PI2	REAL*8	0		/COMMQQ/
X	REAL*8	10702		

```
D Line# 1      7                              Microsoft FORTRAN77 V3.20 02/84
XX      REAL*8            0 *
```

```
                SUBROUTINE DZERO(A,N)
                REAL*8 A(1)
                DO 1 I=1,N
1         1     A(I)=0.D0
                RETURN
                END
```

```
Name     Type        Offset P Class

A        REAL*8           0 *
I        INTEGER*4    10714
N        INTEGER*4        4 *
```

```
                SUBROUTINE DGMPRD(A,B,R,N,M,L)
                REAL*8 A(1),B(1),R(1)
                IR=0
                IK=-M
                DO 10 K=1,L
1               IK=IK+M
1               DO 10 J=1,N
2               IR=IR+1
2               JI=J-N
2               IB=IK
2               R(IR)=0.
2               DO 10 I=1,M
3               JI=JI+N
3               IB=IB+1
3         10    R(IR)=R(IR)+A(JI)*B(IB)
                RETURN
                END
```

```
Name     Type        Offset P Class

A        REAL*8           0 *
B        REAL*8           4 *
I        INTEGER*4    10754
IB       INTEGER*4    10750
IK       INTEGER*4    10726
IR       INTEGER*4    10722
J        INTEGER*4    10738
JI       INTEGER*4    10746
K        INTEGER*4    10730
L        INTEGER*4       20 *
M        INTEGER*4       16 *
N        INTEGER*4       12 *
R        REAL*8           8 *
```

```
                SUBROUTINE DMINV(A,N,D,L,M)
                REAL*8 A(1),D,BIGA,HOLD
                DIMENSION L(1),M(1)
                D=1.0
                NK=-N
                DO 80 K=1,N
1               NK=NK+N
```

```
1          L(K)=K
1          M(K)=K
1          KK=NK+K
1          BIGA=A(KK)
1          DO 20 J=K,N
2          IZ=N*(J-1)
2          DO 20 I=K,N
3          IJ=IZ+I
3    10    IF(DABS(BIGA)-DABS(A(IJ))) 15,20,20
3    15    BIGA=A(IJ)
3          L(K)=I
3          M(K)=J
3    20    CONTINUE
1          J=L(K)
1          IF(J-K) 35,35,25
1    25    KI=K-N
1          DO 30 I=1,N
2          KI=KI+N
2          HOLD=-A(KI)
2          JI=KI-K+J
2          A(KI)=A(JI)
2    30    A(JI)=HOLD
1    35    I=M(K)
1          IF(I-K) 45,45,38
1    38    JP=N*(I-1)
1          DO 40 J=1,N
2          JK=NK+J
2          JI=JP+J
2          HOLD=-A(JK)
2          A(JK)=A(JI)
2    40    A(JI)=HOLD
1    45    IF(BIGA) 48,46,48
1    46    D=0.0
1          RETURN
1    48    DO 55 I=1,N
2          IF(I-K) 50,55,50
2    50    IK=NK+I
2          A(IK)=A(IK)/(-BIGA)
2    55    CONTINUE
1          DO 65 I=1,N
2          IK=NK+I
2          HOLD=A(IK)
2          IJ=I-N
2          DO 65 J=1,N
3          IJ=IJ+N
3          IF(I-K) 60,65,60
3    60    IF(J-K) 62,65,62
3    62    KJ=IJ-I+K
3          A(IJ)=HOLD*A(KJ)+A(IJ)
3    65    CONTINUE
1          KJ=K-N
1          DO 75 J=1,N
2          KJ=KJ+N
2          IF(J-K)70,75,70
2    70    A(KJ)=A(KJ)/BIGA
2    75    CONTINUE
1          D=D*BIGA
1          A(KK)=1.0/BIGA
1    80    CONTINUE
```

```
              K=N
       100    K=(K-1)
              IF(K) 150,150,105
       105    I=L(K)
              IF(I-K) 120,120,108
       108    JQ=N*(K-1)
              JR=N*(I-1)
              DO 110 J=1,N
1             JK=JQ+J
1             HOLD=A(JK)
1             JI=JR+J
1             A(JK)=-A(JI)
1      110    A(JI)=HOLD
       120    J=M(K)
              IF(J-K) 100,100,125
       125    KI=K-N
              DO 130 I=1,N
1             KI=KI+N
1             HOLD=A(KI)
1             JI=KI-K+J
1             A(KI)=-A(JI)
1      130    A(JI)=HOLD
              GO TO 100
       150    RETURN
              END
```

Name	Type	Offset	P	Class
A	REAL*8	0	*	
BIGA	REAL*8	10778		
D	REAL*8	8	*	
DABS				INTRINSIC
HOLD	REAL*8	10830		
I	INTEGER*4	10798		
IJ	INTEGER*4	10806		
IK	INTEGER*4	10858		
IZ	INTEGER*4	10794		
J	INTEGER*4	10786		
JI	INTEGER*4	10838		
JK	INTEGER*4	10850		
JP	INTEGER*4	10842		
JQ	INTEGER*4	10878		
JR	INTEGER*4	10882		
K	INTEGER*4	10766		
KI	INTEGER*4	10822		
KJ	INTEGER*4	10870		
KK	INTEGER*4	10774		
L	INTEGER*4	12	*	
M	INTEGER*4	16	*	
N	INTEGER*4	4	*	
NK	INTEGER*4	10762		

Name	Type	Size	Class
COMMQQ		8048	COMMON
DGMPRD			SUBROUTINE
DMINV			SUBROUTINE

APPENDIX A

WYLE LABORATORIES - RESEARCH STAFF
TECHNICAL MEMORANDUM TM 80-8

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EVALUATION OF SPACE SHUTTLE MAIN ENGINE FLUID DYNAMIC FREQUENCY RESPONSE CHARACTERISTICS

by

T. G. GARDNER

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

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FOREWORD

This report was prepared by Wyle Laboratories, Research and Engineering Division, Huntsville, Alabama, under NASA Contract No. NAS8-33508, for the National Aeronautics and Space Administration (NASA), George C. Marshall Space Flight Center. The contract was administered under the technical direction of the Systems Dynamics Laboratory, with Mr. Harry Bandgren acting as the Technical Contracting Officer's Representative. Mr. Duron Cryder was the contract administrator for NASA.

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EVALUATION OF SPACE SHUTTLE MAIN ENGINE
FLUID DYNAMIC FREQUENCY RESPONSE CHARACTERISTICS

by

T. G. Gardner

ABSTRACT

In order to determine the POGO stability characteristics of the Space Shuttle main engine (SSME) liquid oxygen (LOX) system, an evaluation of the fluid dynamic frequency response functions between elements in the SSME LOX system was performed, both analytically and experimentally. This report acquaints the reader briefly with the POGO testing program and, more specifically, documents, as a user note, the POGO data analysis software. POGO refers to the effect the dynamic interaction between devices in the LOX system has on fluid/mechanical vibration of the system. For the experimental data evaluation, a software package was written for the Hewlett-Packard 5451C Fourier analyzer. The POGO analysis software consists of five separate segments. Each segment is stored on the 5451C disc as an individual program and performs its own unique function. The POGO analysis software includes two separate data reduction methods, a signal calibration, coherence or pulser signal based frequency response function blanking, and automatic plotting features. The 5451C allows variable parameter transfer from program to program. This feature is used to an advantage and requires only minimal user interface during the data reduction process. Experimental results are also included. Comparison of experimental results with the analytical predictions permits adjustments to the general model in order to arrive at a realistic simulation of the POGO characteristics.

SPACE SHUTTLE MAIN ENGINE SYSTEM DESCRIPTION

The Space Shuttle propulsion system consists of two solid rocket boosters (SRBs) and three main engines (SSMEs). The SSMEs are high-performance, liquid-propellant, variable thrust rocket engines, operating at high temperatures, high pressures, and high rotational speeds. Each SSME operates at a chamber pressure of approximately 3000 psia to produce a sea level thrust of 375,000 pounds and vacuum thrust of 470,000 pounds and operates over a range from 50 to 109 percent of the rated power. Each engine consists of ten major components: two preburners, four turbopumps, the hot-gas manifold, the main injector, a heat exchanger, and the main combustion chamber. All other components are attached structurally to the hot-gas manifold, and the entire arrangement is called the SSME powerhead.

A key to the cost effectiveness of the Space Shuttle concept is hardware reusability. As a result, system reliability is of paramount importance. The SSMEs have been subjected to extensive hot firing and flow tests. Under these extreme operating conditions, system failures and malfunctions have occurred due to the self-induced dynamic environment. These failures have ranged from subcritical wear of component bearings to catastrophic explosion and fire resulting from the intense pressure oscillations and dynamic stresses occurring in pumps, valves, and/or propellent lines. The components in the liquid oxygen (LOX) system include the low pressure oxidizer pump (LPOP), POGO suppression system (or accumulator), the high pressure oxidizer pump (HPOP), and the main combustion chamber (MCC). The LOX flows from the external tank (ET) through the above components and is combined with the liquid hydrogen (LH_2) fuel at the inlet of the MCC by the main injector.

The LPOP is an axial-flow pump driven by a six-stage turbine and powered by the LOX. During engine startup and mainstage, the LPOP maintains sufficient pressure in the LOX line to permit the HPOP to operate at high speeds without an inducer and without cavitation, even under worst-case conditions.

The POGO suppressor is a gas-filled accumulator, which serves as a capacitance in the LOX flow circuit. The unit is designed to prevent low-frequency oscillations, transmitted from the Space Shuttle vehicle, from being transmitted into the HPOP and ultimately to prevent MCC pressure oscillations. To provide suppression protection through the startup and shutdown transients, the accumulator is filled with gaseous helium. During normal engine operation, the heat exchanger provides gaseous oxygen (GO_2), as the compliant medium, to the accumulator. The system consists of a 0.6 cubic-foot accumulator, which is attached to the HPOP inlet duct, an internal stand pipe, helium precharge valve package, gaseous oxygen supply valve package, and recirculation isolation valves. The liquid level in the accumulator is controlled by the stand pipe, which is orificed to regulate the GO_2 overflow over the engine operating power level range. Excess gaseous and liquid oxygen are recirculated back to the LPOP inlet through the engine oxidizer bleed duct.

The HPOP consists of two single-stage centrifugal pumps on a common shaft, which is directly driven by a two-stage hot-gas turbine. The main pump receives oxidizer from the LPOP discharge and supplies LOX at increased pressure to the LPOP turbine. The HPOP turbine is powered by hot-gas (hydrogen-rich steam). LOX enters the HPOP main pump through the main pump housing and flows through an inlet with a 50-50 flow split into a double-entry, common outlet impeller. Several sets of guide vanes direct the flow to the impeller inlets. The impeller has four full and four partial blades in each half. After passing through the impeller, the flow is redirected into the HPOP discharge by diffuser vanes. The HPOP is attached to the hot-gas manifold by a flange, which is canted ten degrees out from the engine centerline. The oxidizer then flows into the MCC.

The MCC is a cylindrical structural chamber, which contains the burning propellant gases and is flange-attached to the hot-gas manifold. The MCC consists of a coolant liner, coolant inlet and outlet manifolds, and a structural jacket. The coolant liner, which provides the coolant

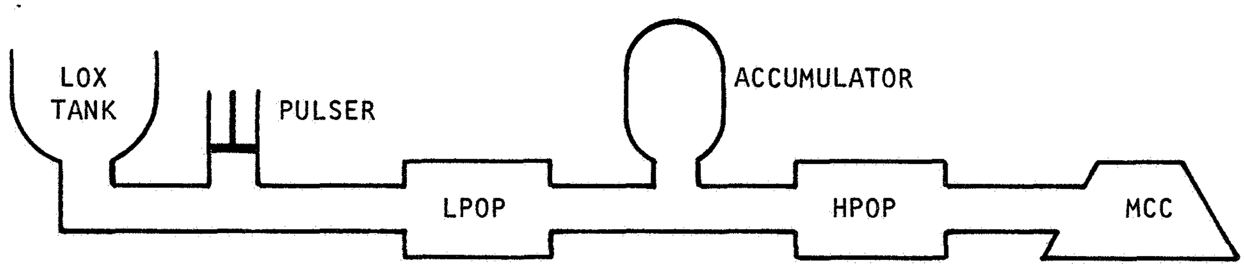
flow path of the MCC, contains 390 milled axial coolant channels, which are ported to the coolant inlet and outlet manifolds. This network provides an up-pass circuit for the liquid hydrogen coolant. The chamber jacket provides the structural strength for the MCC and is approximately 20 inches long. The jacket is formed in two matching halves, which are welded together and to the coolant inlet and outlet manifolds. A throat ring is also welded to the jacket at the MCC throat to provide added strength. The MCC throat follows a contraction from the hot-gas manifold of 2.96:1 and is expanded to a ratio of 5:1 before attaching to the engine nozzle.

In order to validate system performance and ensure equipment reliability, the SSME and components have been and are presently undergoing extensive development and qualification tests. Testing of the engine and components is conducted at several NASA and contractor locations. Full-scale engine test firings for development and flight acceptance are performed on two single-engine test stands at the National Space Technology Laboratories (NSTL), Bay St. Louis, Mississippi, and one stand operated by Rockwell International near Santa Susana, California. In addition, main propulsion testing is performed at NSTL on a stand designed to accommodate the Shuttle main propulsion system element--the three-engine cluster, external tank, and orbiter systems.

Testing is being performed on a continuing basis. The length of a given test is dependent on specific test objectives and may run from several seconds to over 800 seconds. During each test, comprehensive measurements are acquired to monitor system performance, including vibration, dynamic pressure and strain at critical engine locations. Several of these latter measurements are utilized on-line as emergency cutoff indicators, and all are recorded on magnetic tape for subsequent analysis and evaluation.

SPACE SHUTTLE MAIN ENGINE POGO TEST PROGRAM

As part of a program to determine the POGO stability characteristics of the Space Shuttle Main Engine (SSME) liquid oxygen (LOX) system, POGO tests were conducted by Rocketdyne engineers, in California, on the A3 SSME test stand. In order to define the system fluid dynamic characteristics, frequency response functions [H(f)] between various components are calculated from pressure measurements taken at various locations in the system. To calculate the H(f)s, a known pressure signal must be applied to the system and the system response to this signal measured. A pulser was used to generate this dynamic pressure signal, with the tests usually including both sine sweeps and sine dwells. The first device located downstream of the pulser is the low pressure oxidizer pump (LPOP), followed by the accumulator (or suppressor), the high pressure oxidizer pump (HPOP), and the main combustion chamber (MCC). With the accumulator active in the system, the pulser signal is suppressed such that it does not reach the MCC with sufficient strength to be measured adequately. Consequently, tests were conducted with the accumulator active and inactive. The general system diagram below shows the relative location of these devices. Pressure measurements were made at the pulser, the LPOP inlet, the HPOP inlet, and the HPOP discharge.

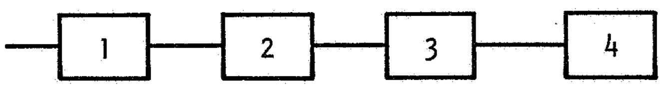


The pulser sine sweeps ranged in frequency from 2 to 40 Hz. At the higher frequencies in the pulser sweep, the displacement of the pulser piston and the corresponding amplitude of the pressure pulse generated were very small. The amplitudes of the pressure signals further down the line were essentially buried in the noise level and very difficult

to measure. For the sine dwells, the magnitude of the pulsed signal can be increased, providing greater dynamic range in the data. The problems associated with the dwell testing are the increased time required to conduct the test and the fact that the frequency response functions can be defined only at the frequencies where the dwells are located. Because of this, a routine that will blank out invalid data in frequency response functions was included in the POGO analysis software. This blanking can be based on either the pulser signal or the coherence function, leaving only the frequency response function data at the frequencies where the pulser was operated. In the initial tests, the dwell frequencies were chosen at approximately 5-Hz intervals. In subsequent tests, the dwells were chosen closer together in order to better define the system frequency response.

POGO DATA ANALYSIS SOFTWARE

For organizational purposes and because of total size, the POGO data analysis software is divided into five segments. Each segment is stored separately on the 5451C disc and runs on the 5451C as an individual program. The 5451C Fourier operating system allows nesting of as many as ten programs. This is the feature that allows these five programs to operate together and perform the total POGO data analysis. The software includes two frequency response function [H(f)] calculation routines. These two data reduction methods are referred to as the RATIO and DIRECT methods for calculating frequency response functions. In the RATIO technique, all H(f)s are initially referenced to the pulser. These H(f)s are then divided, with the resulting quotient being the H(f) across various combinations of devices. For example, the H(f) between devices 2 and 3 in the following schematic may be calculated as the RATIO of the H(f) between devices 1 and 3 and the H(f) between devices 1 and 2.



$$H(f)_{3/2} = \frac{H(f)_{3/1}}{H(f)_{2/1}},$$

where $H(f)_{n/1} = \frac{G_{n1}}{G_{11}}$ and n = output, 1 = input [1, 2]. Here G_{n1} is the cross spectrum between the input and output, and G_{11} is the autospectrum of the input (pulser).

> NOTE: The POGO software outputs the auto (power) spectra and cross (power) spectra as functions normalized to the bandwidth (Δf) or as power spectral densities (PSDs) and cross-power spectral densities (XPSDs). However, the 5451C calculates and uses the functions in their nonnormalized form to calculate frequency response functions [H(f)s] and coherence functions [γ^2(f)s] [2]. In the remainder of this document, all spectral functions will be referred to as PSDs and XPSDs regardless of their actual state of normalization. The reader should understand that all H(f) and γ^2(f) calculations are made prior to normalization.

To calculate the $\gamma^2(f)$ that is compatible with the RATIO H(f), the following formula is used [3]:

$$\gamma^2(f)_{3/2} = \frac{1}{\dfrac{1}{\gamma^2(f)_{3/1}} + \dfrac{1}{\gamma^2(f)_{2/1}} - 1}$$

where $\gamma^2(f)_{n/1} = \dfrac{|G_{n1}|^2}{G_{11}G_{nn}}$, and n and 1 are output and input, as above [1, 2].

To arrive at $H(f)_{3/2}$ and $\gamma^2(f)_{3/2}$ using the direct method involves calculating the frequency response function as the XPSD, between devices 3 and 2, and divided by the PSD of device 2. The coherence is calculated as the magnitude squared of the XPSD divided by both the input and output PSDs. These equations are as follows:

$$H(f)_{3/2} = \frac{G_{32}}{G_{22}}$$

$$\gamma^2(f)_{3/2} = \frac{|G_{32}|^2}{G_{22}\ G_{33}}$$

where G_{32} = XPSD, G_{22} = input PSD, and G_{33} = output PSD.

The POGO software also calculates frequency response functions, both RATIO and DIRECT, which have been blanked, based on either the coherence or the pulser signal. Blanking means that the frequency response function magnitude and phase are set to zero at those frequencies where the value of the coherence, or pulser signal, does not exceed the user set minimum.

As previously stated, the POGO analysis software consists of five segments, each of which is stored on the 5451C disc in a separate keyboard program file (KPF) record. They are currently stored in successive records (1 - 5) on the Marshall Space Flight Center, Systems Dynamics Lab's 5451C Fourier software disc.

KEYBOARD PROGRAM FILE, RECORD 1

KPF1 contains part 1 of three parts, which perform the RATIO calculations. Part 1 sets up the data block size, calibration factors, total amount of data to be taken, and delta f (Δf) [frequency resolution or bandwidth]. This information is used to calculate both the RATIO and DIRECT H(f)s. The 5451C has a block arithmetic mode, which allows any block of data to be multiplied or divided by any number. This number, however, must be an integer. If this number happens to be a floating-point variable parameter (VP), the 5451C simply truncates any part of the VP that lies to the right of the decimal. In reference to this problem, the POGO analysis software first multiplies each calibration factor by 100, then calibrates the appropriate data block, and finally divides the data block by 100. This allows for two decimal places in each calibration factor. The same type procedure is used with regard to the VP that holds the Δf parameter, to allow for one digit to the right of the decimal when calculating PSDs. After the initial setup, KPF1 reads the analog data from the tape and stores it on the ADC Throughput File, beginning at record 0. KPF1 then retrieves this time domain data, two channels at a time, and calculates PSDs for each channel. KPF1 also calculates H(f), $\gamma^2(f)$, and XPSDs for the three pairs, LPOP/pulser, HPOP/pulser, and MCC/pulser. This data is stored in data blocks 12 through 27. Program control is then transferred to KPF2, which is part 2 of the POGO analysis software.

KEYBOARD PROGRAM FILE, RECORD 2

KPF2 begins the calculations for the RATIO H(f)s and $\gamma^2(f)$s. The 5451C has preprogrammed keys that will perform the arithmetic necessary to make these calculations. The keys, however, perform what will be referred to as block arithmetic. The 5451C stores data in blocks internally, in a format Hewlett-Packard calls floating-point-by-block. This means that the data block is actually a group of integers, all with a common scale factor. Because of this method of data handling, the arithmetic operation performed by the block command is not floating point, but is integer arithmetic. These operations involved in the

RATIO calculations are limited to a 40-dB dynamic range. When inverting a number, as that number approaches zero, the inverse approaches infinity. It becomes apparent that if there are any numbers whose value is less than 0.01 in a data block, any number greater than or equal to 1 will be more than 40 dB down when that block is inverted. The 5451C automatically scales up the block scale factor to eliminate overflowing, which causes any number more than 40 dB down to be set to zero. This is a serious problem when doing the type of calculation involved in arriving at the RATIO H(f)s and $\gamma^2(f)$s. In both of these calculations, especially the $\gamma^2(f)$ calculation, the quotient in the formulations is dominated by the small numbers in the denominator. These small numbers are not reliable data points, and the valid data is lost below the 40-dB dynamic range.

The problem was solved in this program by using a floating-point arithmetic scheme in the $\gamma^2(f)$ calculations and a combination of floating-point arithmetic and a filtering technique in the H(f) calculations. The floating-point scheme involves extracting each channel (or data point) point-by-point from a data block, putting the value into a floating-point format (via a floating-point variable parameter), executing the arithmetic operation, and finally putting the datum back into the data block. A magnitude filtering technique is used in the H(f) calculation to eliminate a loss of data after the values are put back into the data block. The real and imaginary parts of the H(f) are filtered so that any values outside the range of ± 7 are set to zero. This allows a polar magnitude maximum of 10. The 40-dB dynamic range then will be 10^{-1} to 10^{1}. This filtering technique is not necessary in the $\gamma^2(f)$ calculations because of the final quantity inversion in the formulation. All the values to be inverted, however, are scanned for values of identically zero before inversion. This is to eliminate any numbers actually going to the upper limit (infinity).

The program loops through the above operation enough times to calculate the RATIO H(f) and $\gamma^2(f)$ for each channel in the data block. This loop is nested inside a loop, which allows for all three sets of ratio

calculations to be computed. Part 2 of the POGO analysis software then transfers control to part 3.

KEYBOARD PROGRAM FILE, RECORD 3

KPF3 defines the variable parameter, corresponding to the ratio calculations, necessary to operate the plot routine. KPF3 also performs the calculations involved in the H(f) blanking routine. KPF3 has several entry points, which allow various operations to be performed outside the normal program flow. KPF2 flows into the beginning of KPF3, which jumps to the blanking routine. The blanking routine begins by prompting the user to establish whether the blanking will be based upon the $\gamma^2(f)$ or the pulser PSD. The user will enter either a zero, to establish coherence blanking, or a two, to define pulser blanking. This number (0 or 2) will also be used to establish which labels will be given to the plots of the blanked H(f)s during the plot routine. If pulser blanking is chosen, KPF3 will display the pulser PSD to allow the user an opportunity to view the signal and decide on the minimum value used for the blanking routine. If $\gamma^2(f)$ blanking is chosen, KPF3 skips directly to the next step, which is a prompt, asking for the minimum value in the blanking routine. Next, KPF3 sets up the block that will be used for generating the blanked H(f). KPF3 then enters the blanking loop. This loop operates individually on each channel in the frequency domain data block. In this loop, KPF3 goes to either the pulser or $\gamma^2(f)$ block and gets one channel at a time, beginning with channel one (channel zero is the first channel) and ending with the next to last channel in the data block. The value of this channel is compared with the values of the channel immediately preceding and the channel immediately following. If the value of the channel in question is greatest, it is determined to be a local maximum. The value is then compared with the minimum value specified earlier by the user. If the value of this channel is greater in all three tests, it is chosen as a channel of interest. The corresponding channel in the H(f) data block is gathered into a complex variable parameter and stored in the data block that was prepared previously for the blanked H(f). When the loop is complete, the blanked H(f) will consist of calculated H(f) data only at those frequencies where the

pulser or $\gamma^2(f)$ passed all the necessary tests. The remainder of the blanked H(f) block will be filled with zeros. Because the HP 5451C stores frequency domain data with both real and imaginary information in a combined complex channel, the blanked H(f) contains blanked phase information as well as blanked magnitude. KPF3 then loops three times to generate a blanked version of each H(f), HPOP/LPOP, MCC/HPOP, and MCC/LPOP. KPF3 then jumps to the section that defines the variable parameters necessary to run the plot program. Finally, KPF3 transfers control to KPF5, the POGO plot routine.

KEYBOARD PROGRAM FILE, RECORD 4

KPF4 is a single-part program, which calculates the H(f)s, HPOP/LPOP, MCC/HPOP, and MCC/LPOP by matching the outputs and inputs "directly" rather than ratioing H(f)s, which have all been referenced to the pulser. This program (KPF4) uses several variable parameters, which must have been previously defined by running the first three files containing the RATIO software. These variable parameters are VP1 = block size; VP2 = number of ADC Throughput records; VP2000 through VP2003 = calibration factors for channels A through D, respectively; VP2004 = frequency resolution (Δf); and VP2030 = minimum value for the blanking routine. KPF4 also retrieves time domain data from the ADC Throughput File. These data must have been written previously on the disc (starting with record zero) via KPF1 (RATIO software, part 1). The data may be written to the disc and the necessary variable parameters defined independently of the RATIO software. It is recommended, however, that all programs be operated in sequence. The direct POGO analysis software (KPF4) writes over the data blocks generated via the RATIO software. This program therefore should not be initiated until all the required ratio data blocks have been reproduced. These data blocks include all PSDs and XPSDs (ref. pulser), which are not recalculated by the DIRECT software. Immediately after clearing the data blocks, KPF4 begins a loop that operates three times. The loop reads the correct data channels from the disc, Fourier transforms the data, calibrates the data, and calculates averaged PSDs via the special subroutine of the 5451C. KPF4 then calculates the H(f) and $\gamma^2(f)$ from the

averaged PSD data. The H(f), γ^2(f), and XPSDs are then stored in the appropriate data blocks. (See "DIRECT POGO Program Menu," appendix C.)

KPF4 now transfers control to KPF3 at the point where the H(f) blanking loop begins. Before jumping to KPF3, KPF4 defines the variable parameters that describe the location of the DIRECT H(F)s. Once in KPF3 the blanked H(f)s are calculated using the same minimum value specified by the user during the RATIO calculations. If the user has entered the POGO software in the DIRECT calculations and wishes to change the minimum blanking value, the user simply jumps to label 43 of KPF4.

Upon returning from the blanking routine, KPF4 defines the variable parameters necessary to operate the POGO plot program (KPF5). KPF4 then transfers control to the plot routine.

KEYBOARD PROGRAM FILE, RECORD 5

KPF5 is entitled "POGO Plot Software." This software operates with both the RATIO and the DIRECT software. KPF5 uses several variable parameters that must be defined by the respective software whose data is to be plotted. The program is organized into several separate routines, including a plot routine, a hard copy routine, a delay routine, and a routine that sets up and plots all the H(f)s in three different formats. The program sets up and automatically plots all the data generated by the respective RATIO and DIRECT programs. The KPF5 prints a data block menu and allows the user to replot any of the data blocks. The plot program is geared to run with a Tektronics 4052 graphics terminal and a Tektronics hard copy unit. Because of various incompatibilities between the 5451C and the Tektronics terminal with respect to the time required to transmit plot commands and the time required to execute them, a delay routine is incorporated in the plot program. This subroutine simply counts from one to 50 and returns. The routine is called in several locations where a time delay between plot commands is necessary.

The plot program uses several variable parameters that establish which program (RATIO or DIRECT) has generated the data being plotted. The

plot program also labels each plot with test ID information in the upper right-hand corner of the plot. This information is stored as message number one in each of the text buffers one and two. Text buffer #1 is used for the RATIO data, while text buffer #2 is used with the DIRECT data. Message #1 should be changed for each new set of test data. The message may be changed by executing the following set of operations from the 5451C terminal:

Step #	Command	5451C Status
1	Y 5403 (n1)	busy

This command calls text buffer n1 (1 for RATIO, 2 for DIRECT) into the computer core and activates the editing commands.

2	/R01	busy

This command tells the 5451C to replace message #1.

3	01	busy
4	(Test ID)	busy
5	/*	busy

This sequence of commands results in the test ID being recognized as message 01. The /* defines the end of the message.

6	/	busy

This command terminates the text buffer edit mode.

To allow the user to enter the program flow for special purposes, the POGO software has many labels throughout the five KPFs. Listed below are the various jump commands and their uses.

J 0 1

This command starts the POGO software, initially setting up the calibration factors, etc, and reading the analog data.

J 10 1

This command enters POGO Software Part 1 after all the initial values have been entered and the analog data has been stored on disc in the ADC Throughput File. If this command is to be executed, the user must first be sure that the variable parameters that contain the values for the blocksize, calibration factors, number of records of data, and frequency resolution (Δf) are defined correctly and that the correct time domain data is stored on the ADC Throughput File.

J 20 2

This command begins the RATIO calculations for H(f)s and γ^2(f)s. This command may be executed if the proper data blocks reside in core in the correct block numbers. The data blocks necessary are

H(f)	LPOP/Pulser	Block 12
γ^2(f)	"	Block 13
H(f)	HPOP/Pulser	Block 14
γ^2(f)	"	Block 15
H(f)	MCC/Pulser	Block 16
γ^2(f)	"	Block 17

H 30 3

This command may be used when the user wishes to recalculate the blanked RATIO frequency response functions. The user will have the opportunity to re-establish the type of blanking [pulser or γ^2(f)] and/or the minimum value for that blanking. The RATIO autoplot parameters are defined and the program control is transferred to the plot routine.

J 31 3

This command is preliminary to the POGO Plot Routine. This command enters KPF3 and defines the variable parameters necessary to run the automatic plot portion of the plot routine. After these parameters are defined, program control is automatically transferred to the plot routine. This command should be used only when the user wishes to enter the autoplot routine with RATIO data blocks. This command might be useful if, for example, the user wants to change the test ID message in the RATIO text buffer after the POGO software has completed the data calculations. The user can stop program execution and edit the text buffer, then return to the autoplot sequence.

J 40 4

This command begins the DIRECT POGO Software. This should be used only after the RATIO program has been run, defining the appropriate variable parameters, and writing the time domain data on the ADC Throughput File.

J 43 4

This command enters KPF4 where necessary variable parameters are defined just prior to transferring control to the H(f) blanking routine in KPF3. This command will allow the user to calculate DIRECT blanked H(f)s.

J 44 4

This command causes the computer to begin execution in KPF4 at the point where the variable parameters that control the auto-plot routine for DIRECT data blocks are defined. Program control is automatically transferred to the plot routine.

J 53 5

This command will cause the plot program to display on the terminal the appropriate menu corresponding to the data stored in the data blocks. The plot program prompts the user to set the display scale as desired, then press the continue button to allow the program to plot the data block on the graphics terminal. This command is useful when the user wishes to return to the plot program after the machine has been idled and the plot routine pointers have been changed.

Appendix A describes the flow of the POGO software. Appendix B contains a complete list of all the program steps along with a description of each. Appendix C contains a listing of the text record messages used with the POGO software. Appendix D contains a listing of both text buffers used with the POGO software. Appendix E contains sample data output from the POGO software.

REFERENCES

1. Bendat, J. S., and A. G. Piersol. *Random Data: Analysis and Measurement Procedures*. John Wiley & Sons, New York, 1971.

2. Schiesser, W. E. Statistical Uncertainty of Frequency Response Determined from Random Signals. Weston-Boonshaft and Fuchs, NASA Bulletin 711-C2.

3. Hewlett-Packard. 5451C Fourier Analyzer System Manual (Binder No. 1). Mar. 1979.

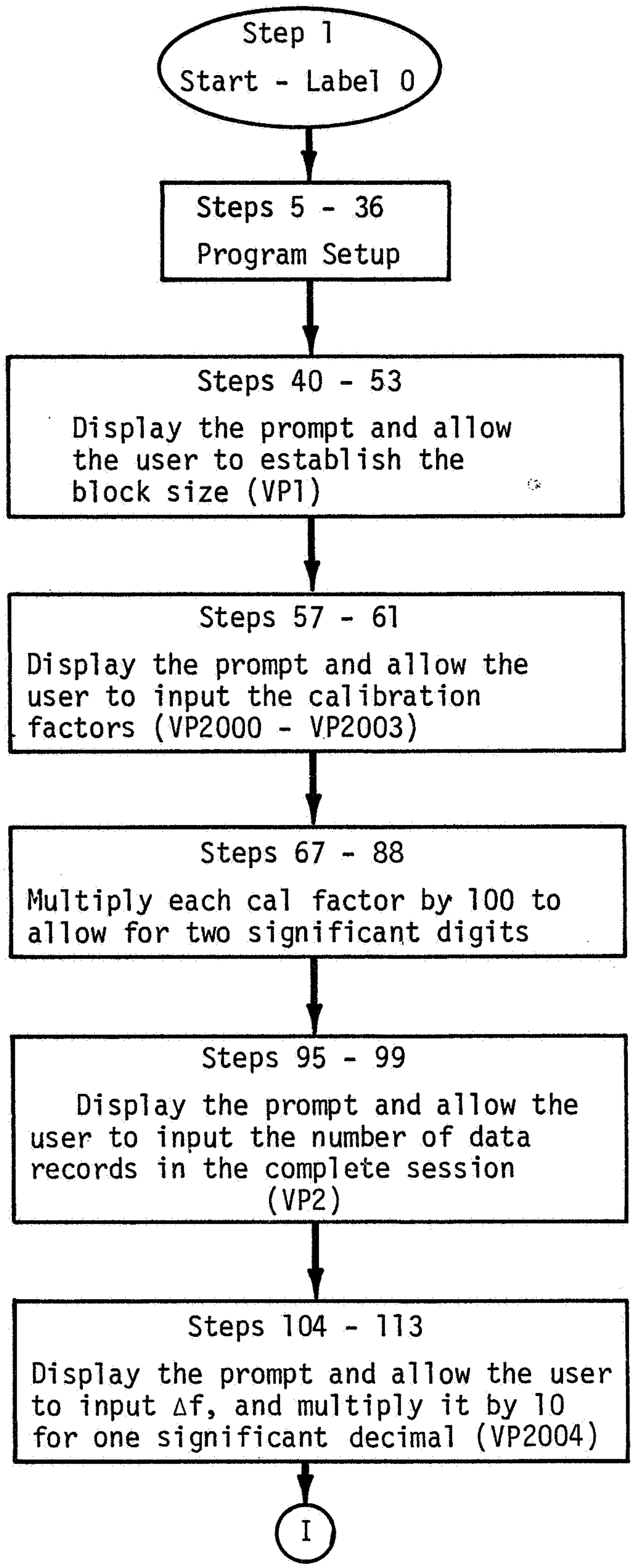
APPENDIX A

POGO SOFTWARE FLOWCHART

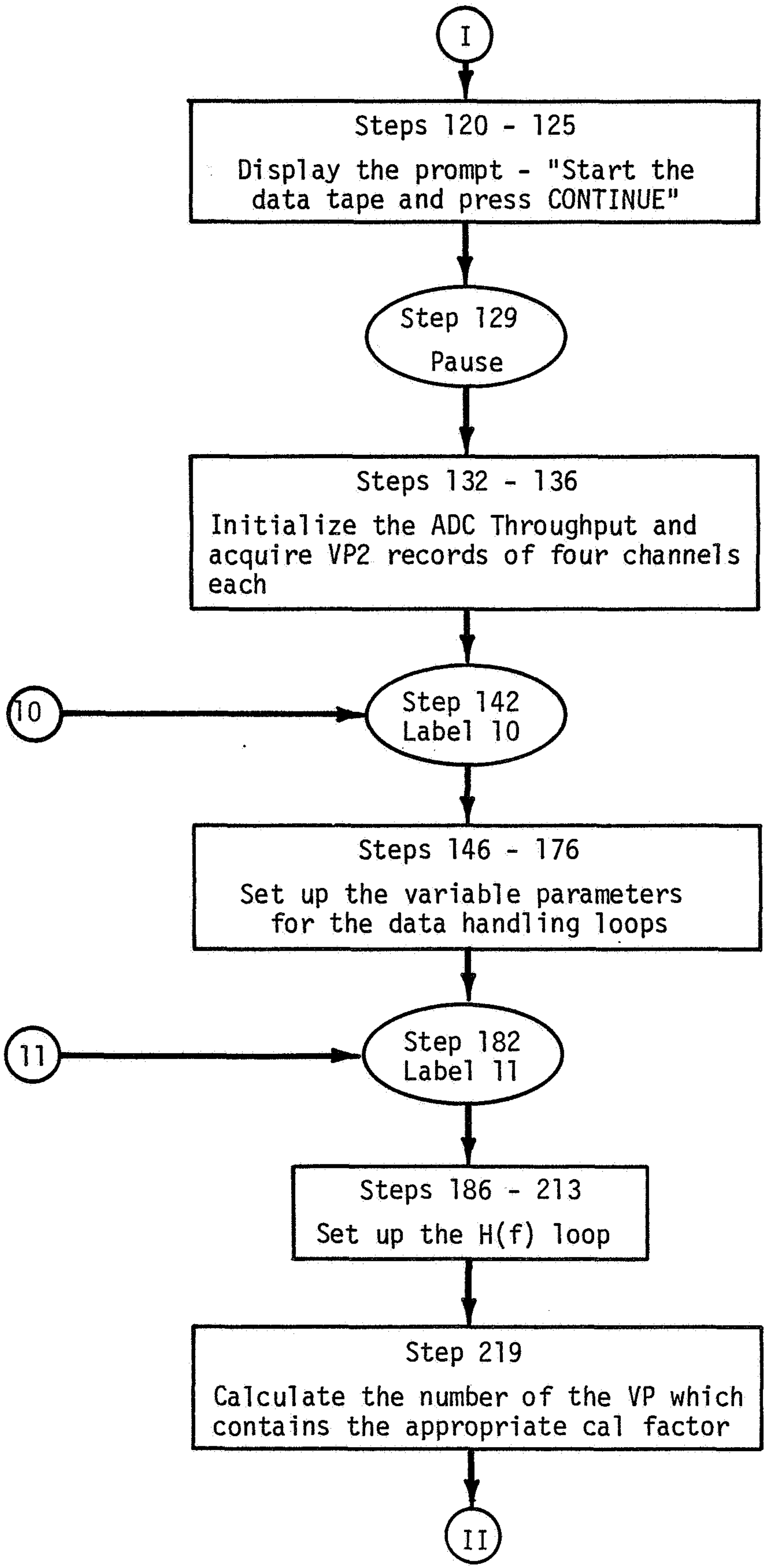
APPENDIX A

POGO SOFTWARE FLOWCHART

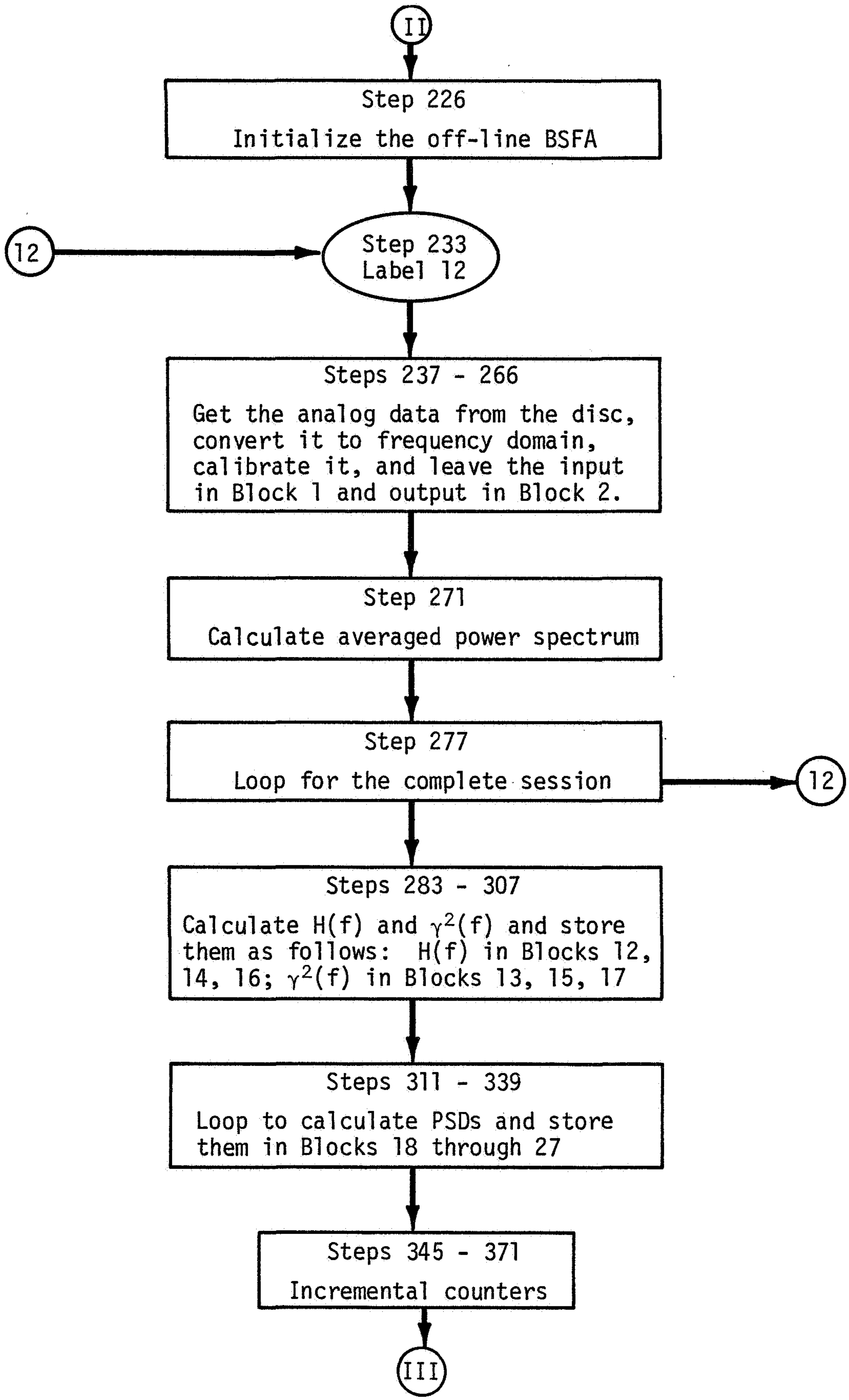
RATIO POGO SOFTWARE - PART 1 FLOWCHART



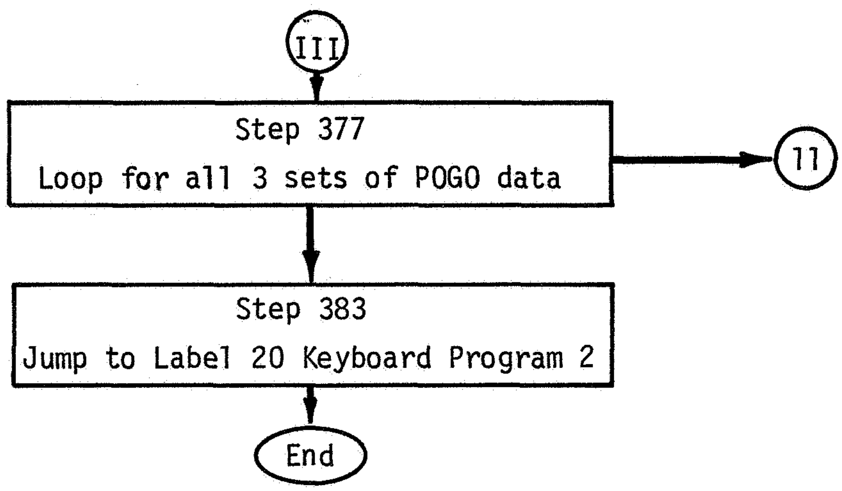
RATIO POGO SOFTWARE - PART 1 FLOWCHART (Continued)



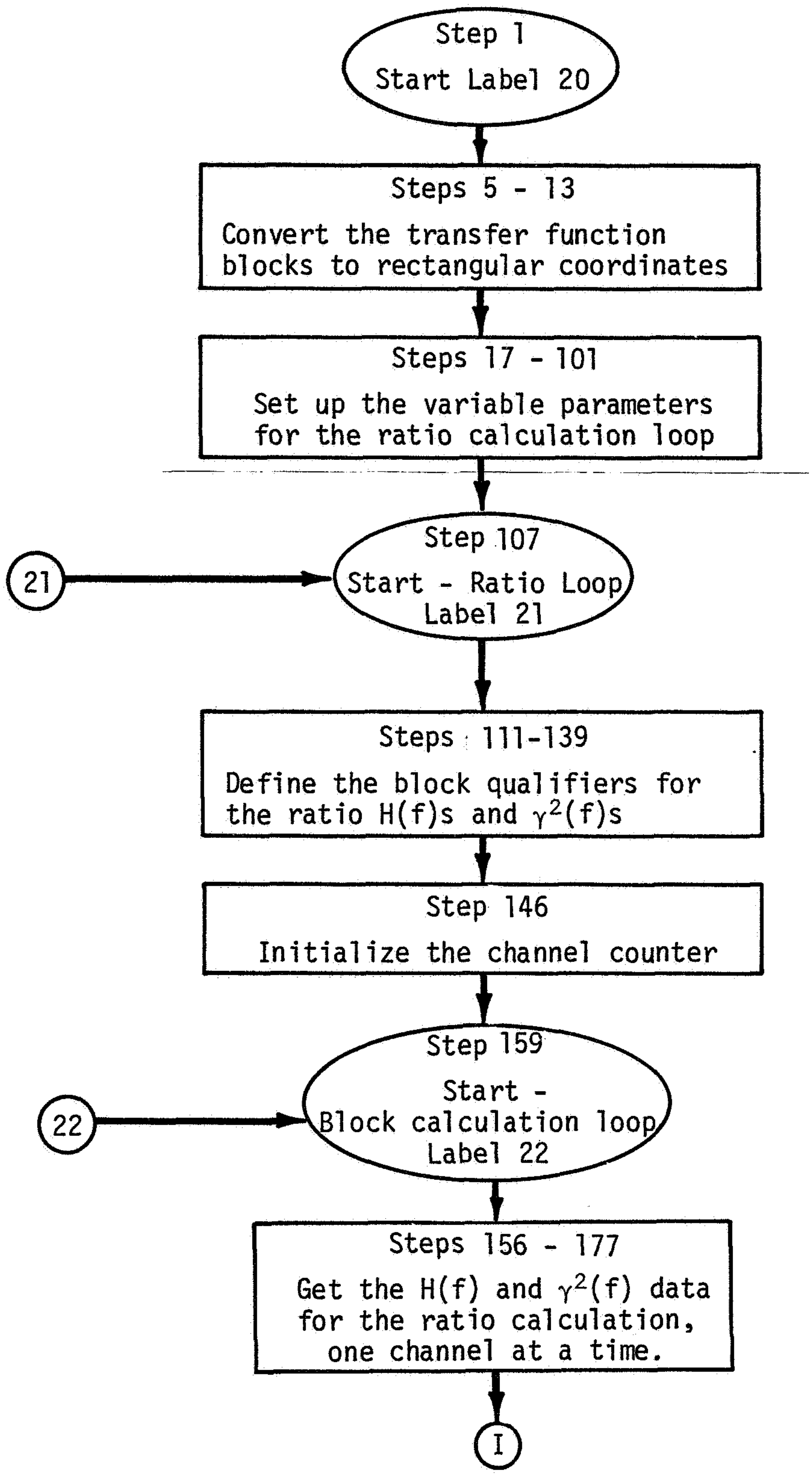
RATIO POGO SOFTWARE - PART 1 FLOWCHART (Continued)



RATIO POGO SOFTWARE - PART 1 FLOWCHART (Concluded)

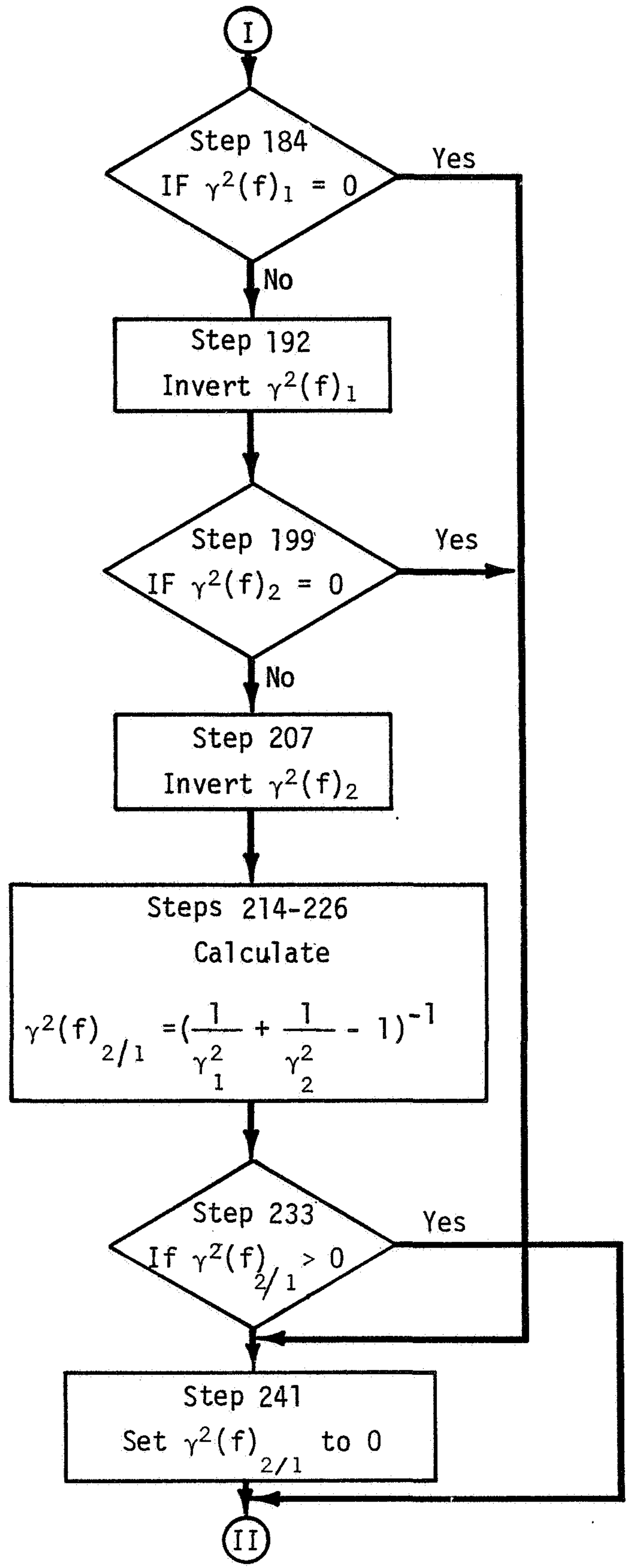


RATIO POGO SOFTWARE - PART 2 FLOWCHART

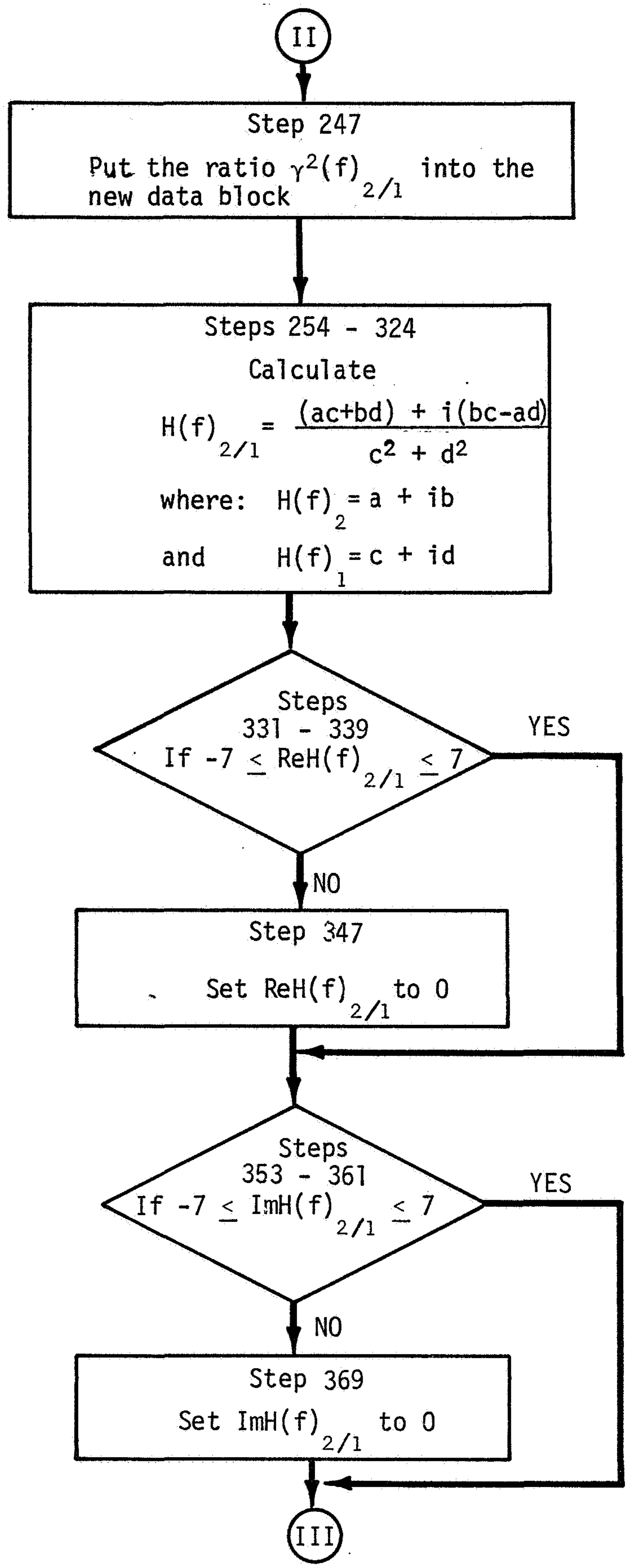


A6

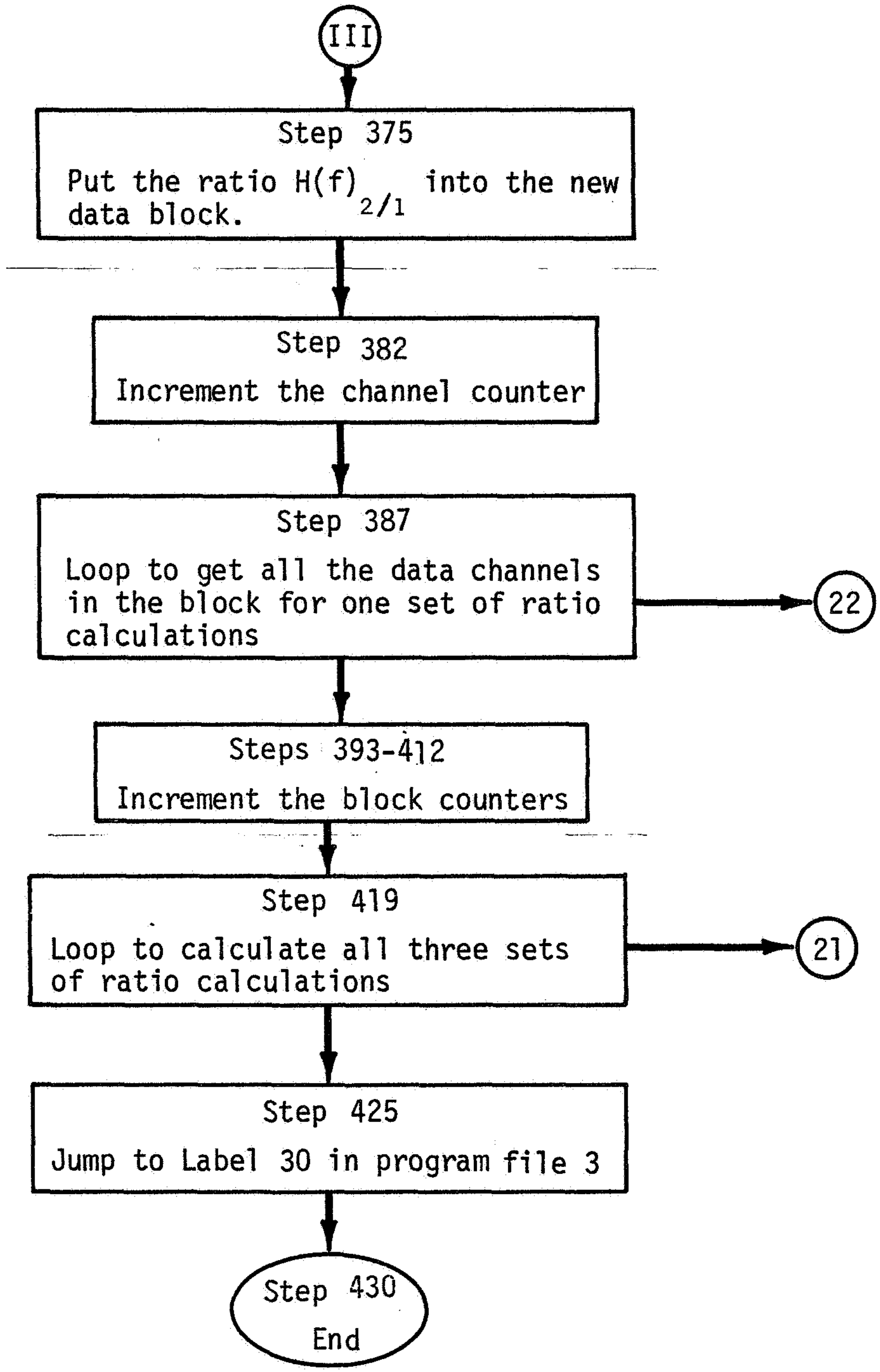
RATIO POGO SOFTWARE - PART 2 FLOWCHART (Continued)



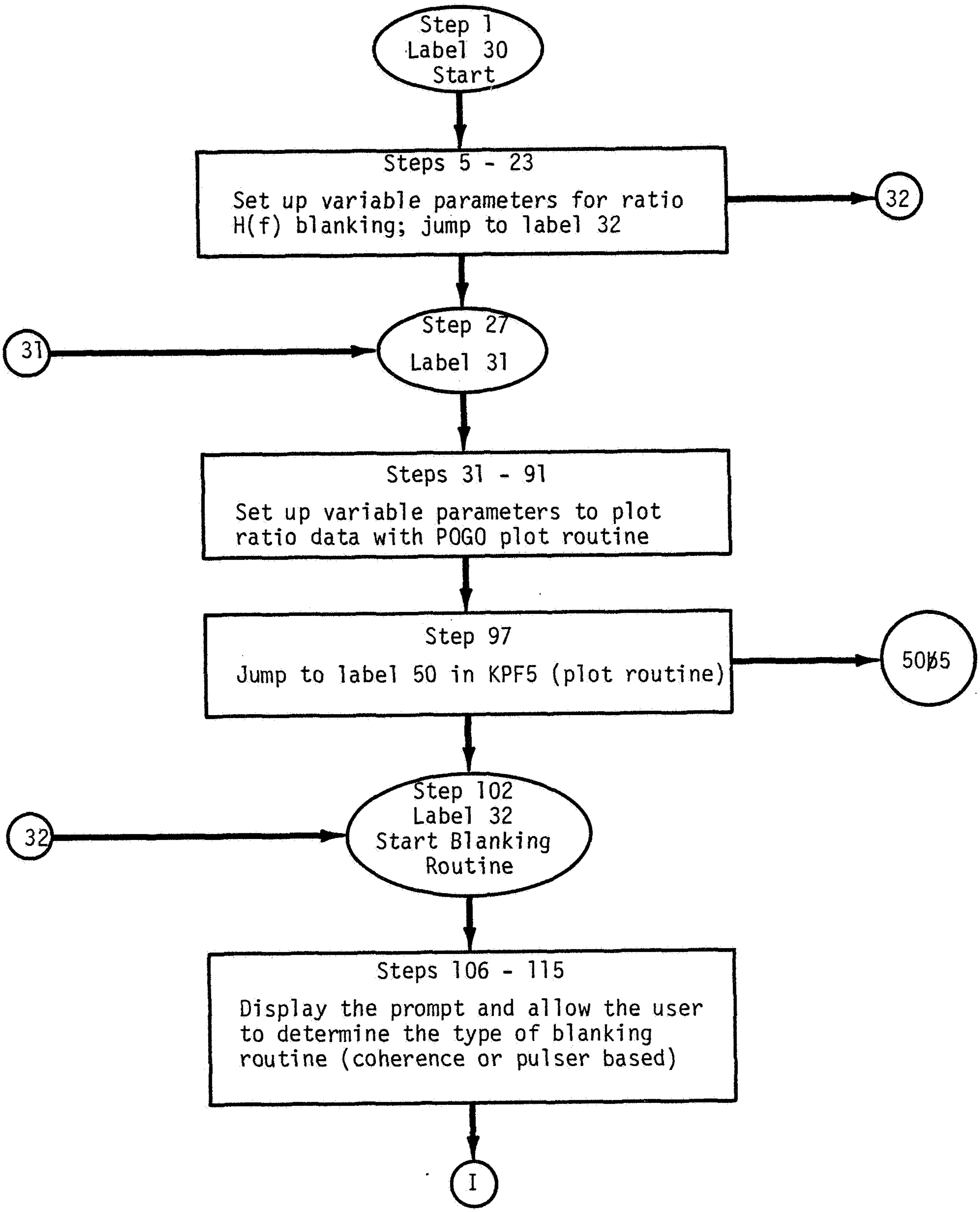
RATIO POGO SOFTWARE - PART 2 FLOWCHART (Continued)



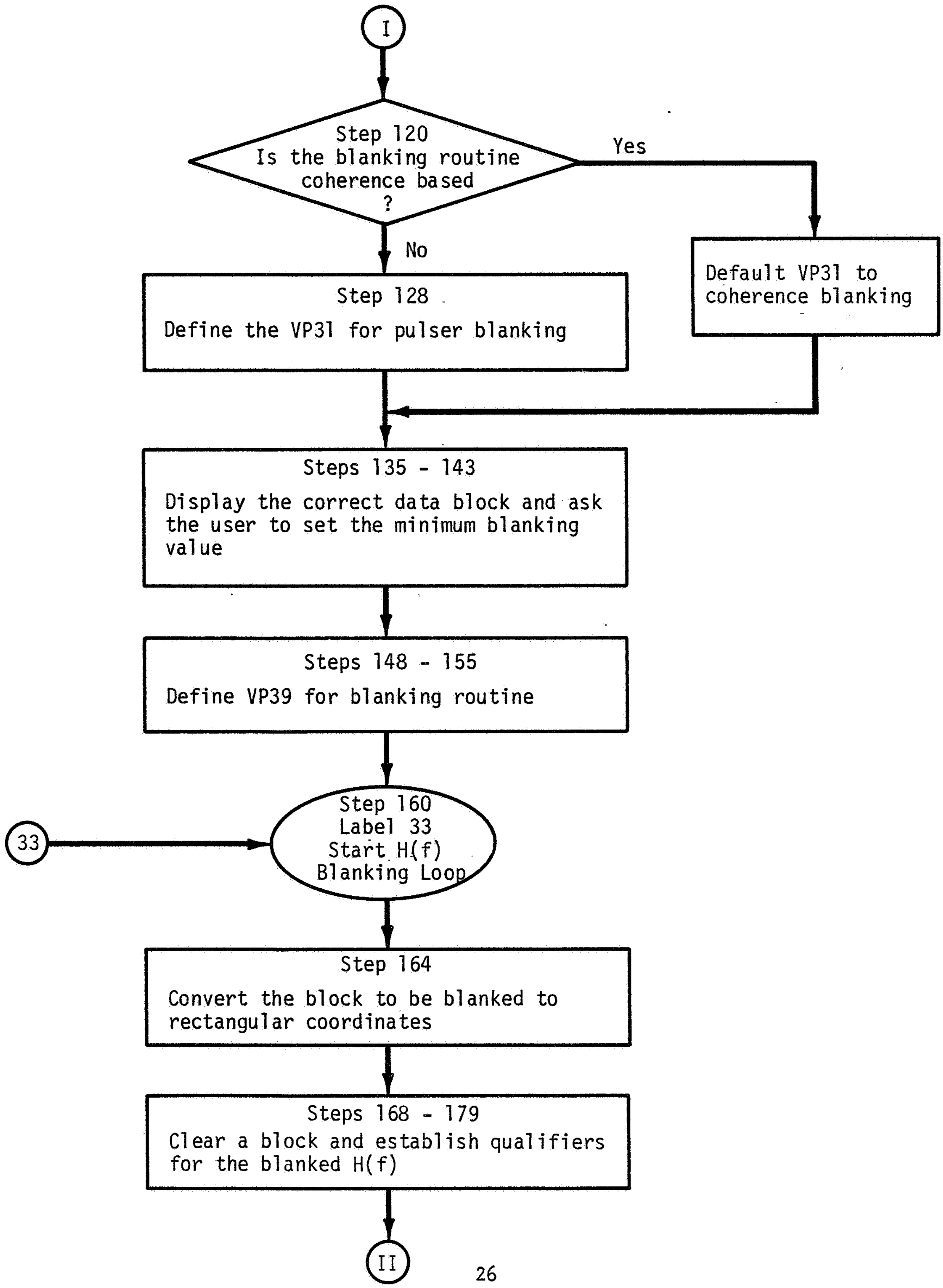
RATIO POGO SOFTWARE - PART 2 FLOWCHART (Concluded)



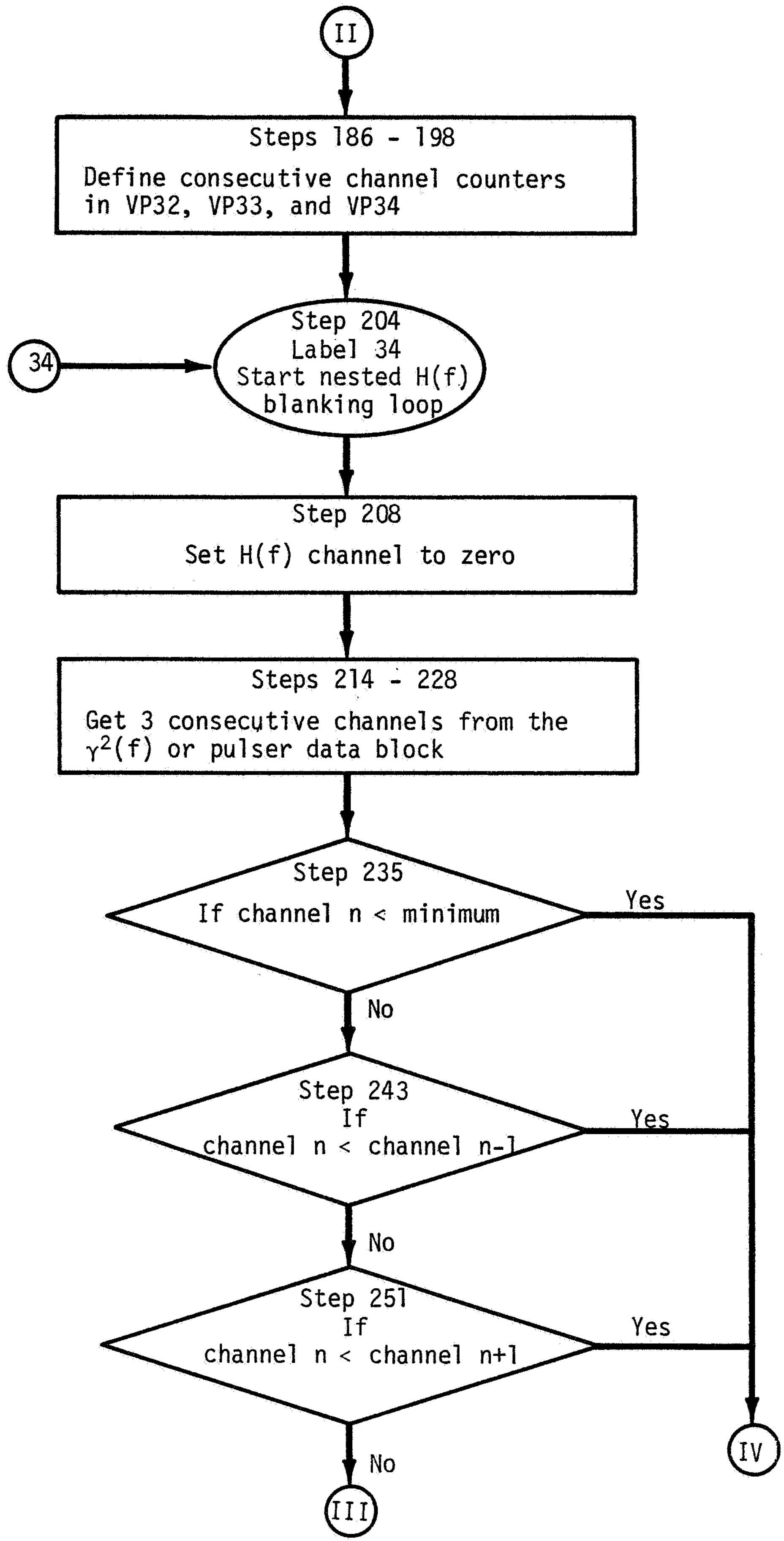
POGO SOFTWARE BLANKING ROUTINE



POGO SOFTWARE BLANKING ROUTINE (Continued)

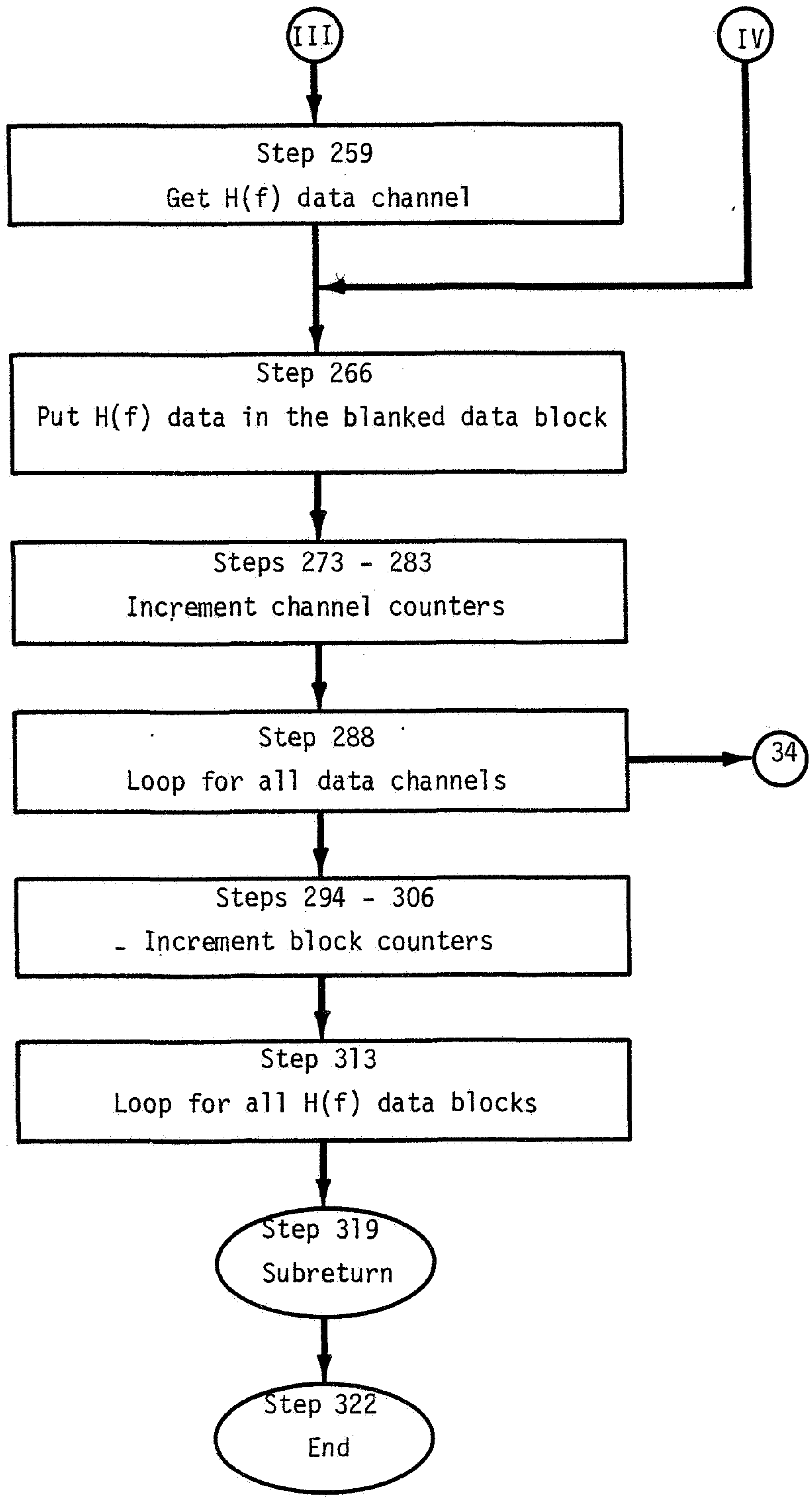


POGO SOFTWARE BLANKING ROUTINE (Continued)

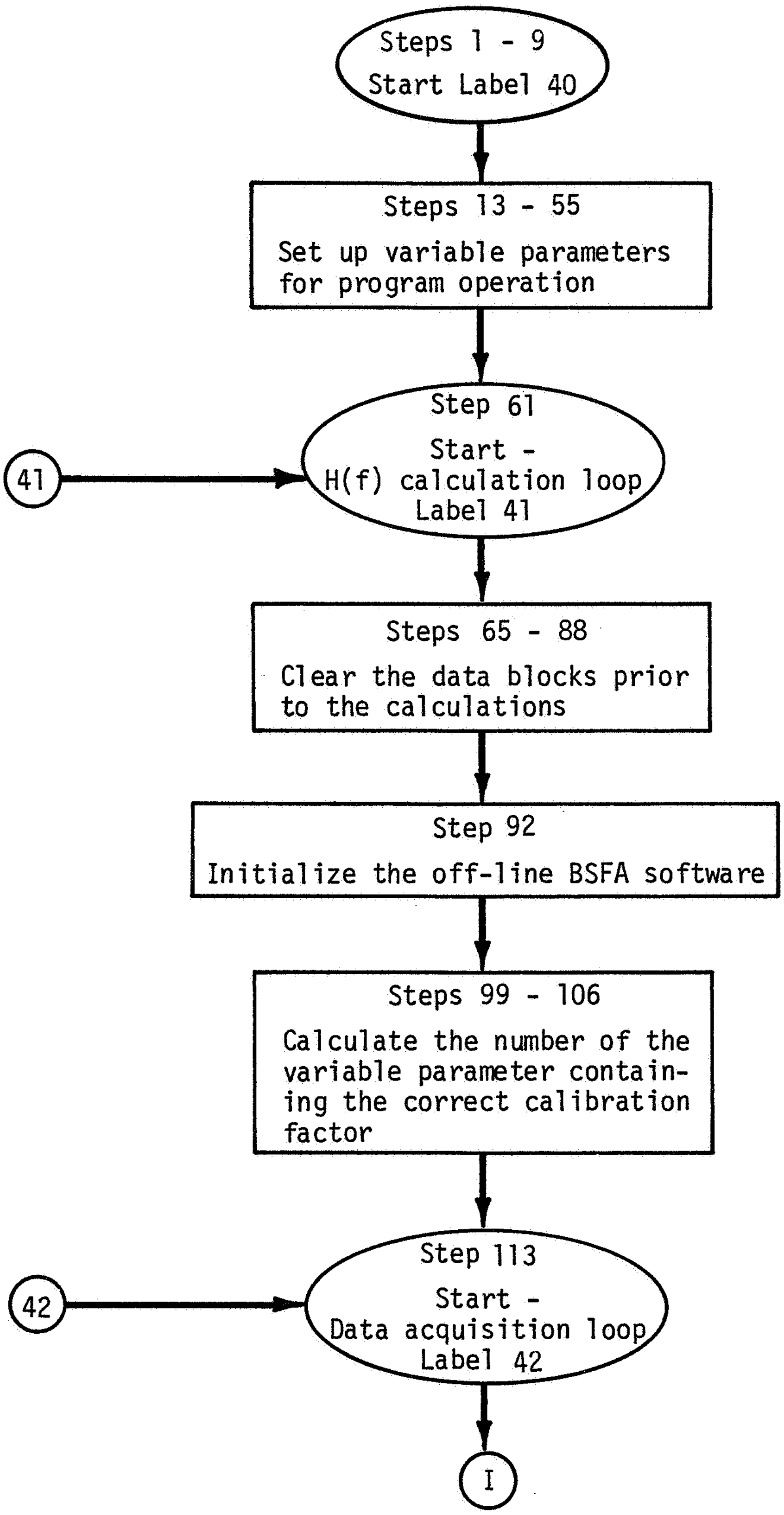


A12

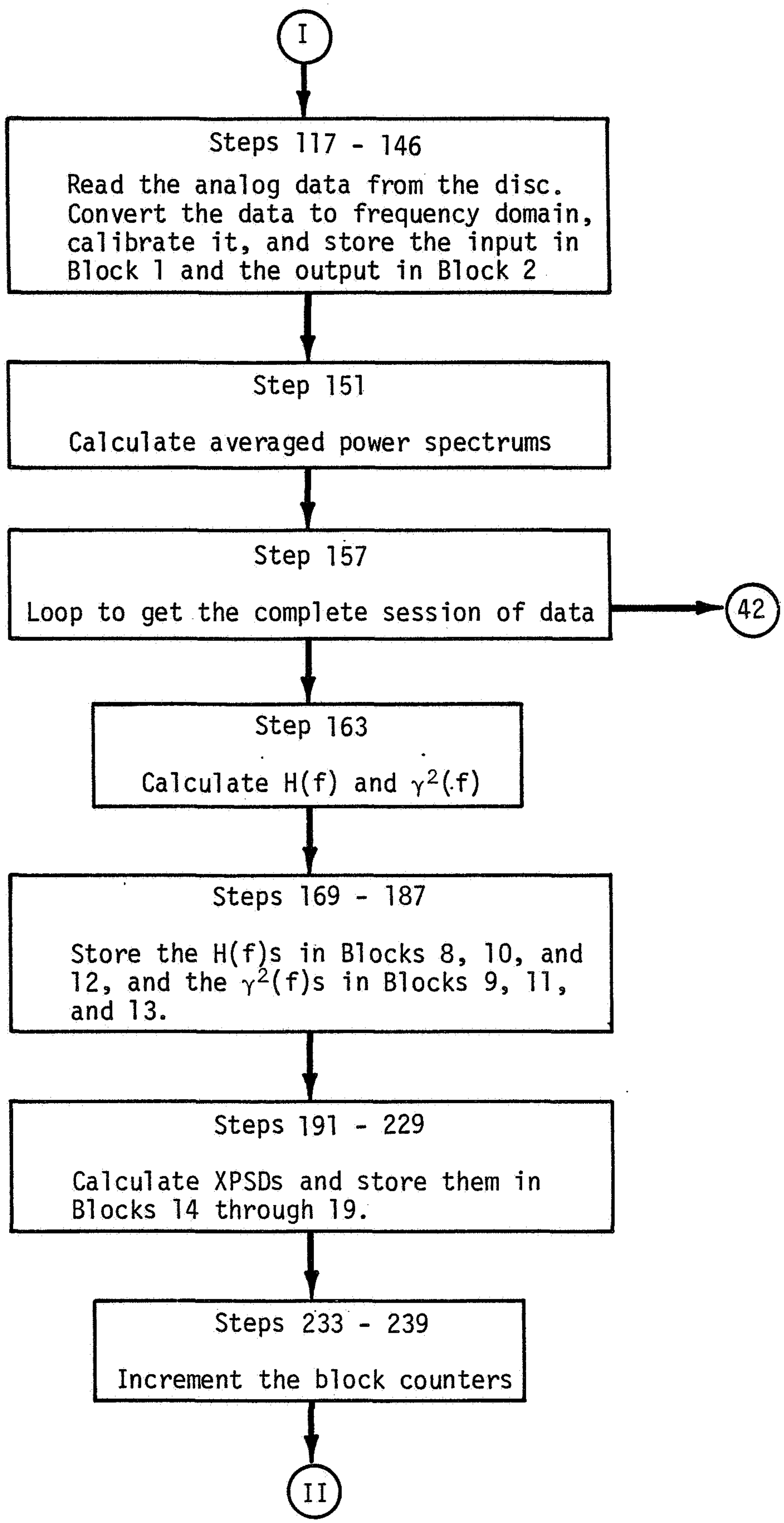
POGO SOFTWARE BLANKING ROUTINE (Concluded)



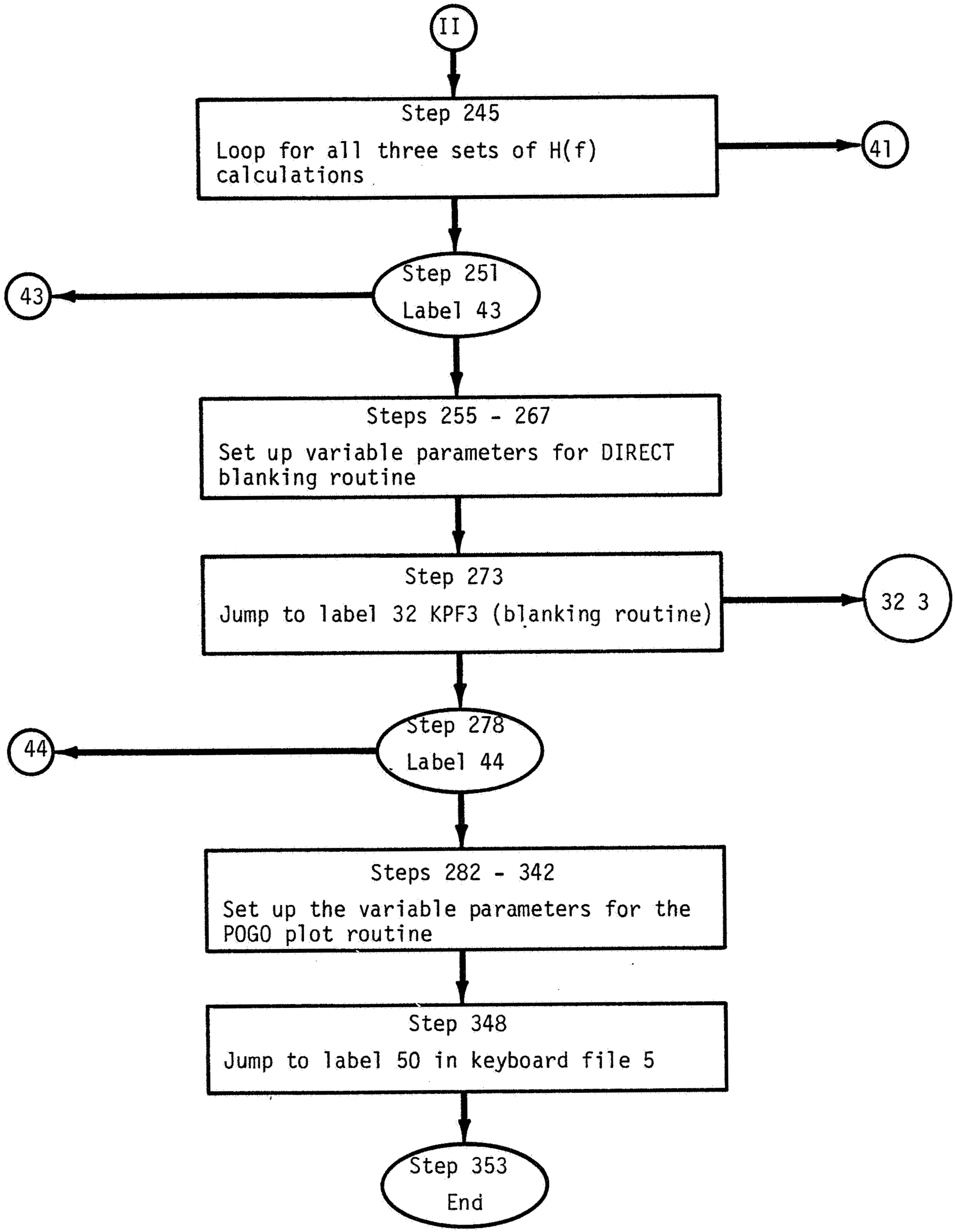
DIRECT POGO SOFTWARE FLOWCHART



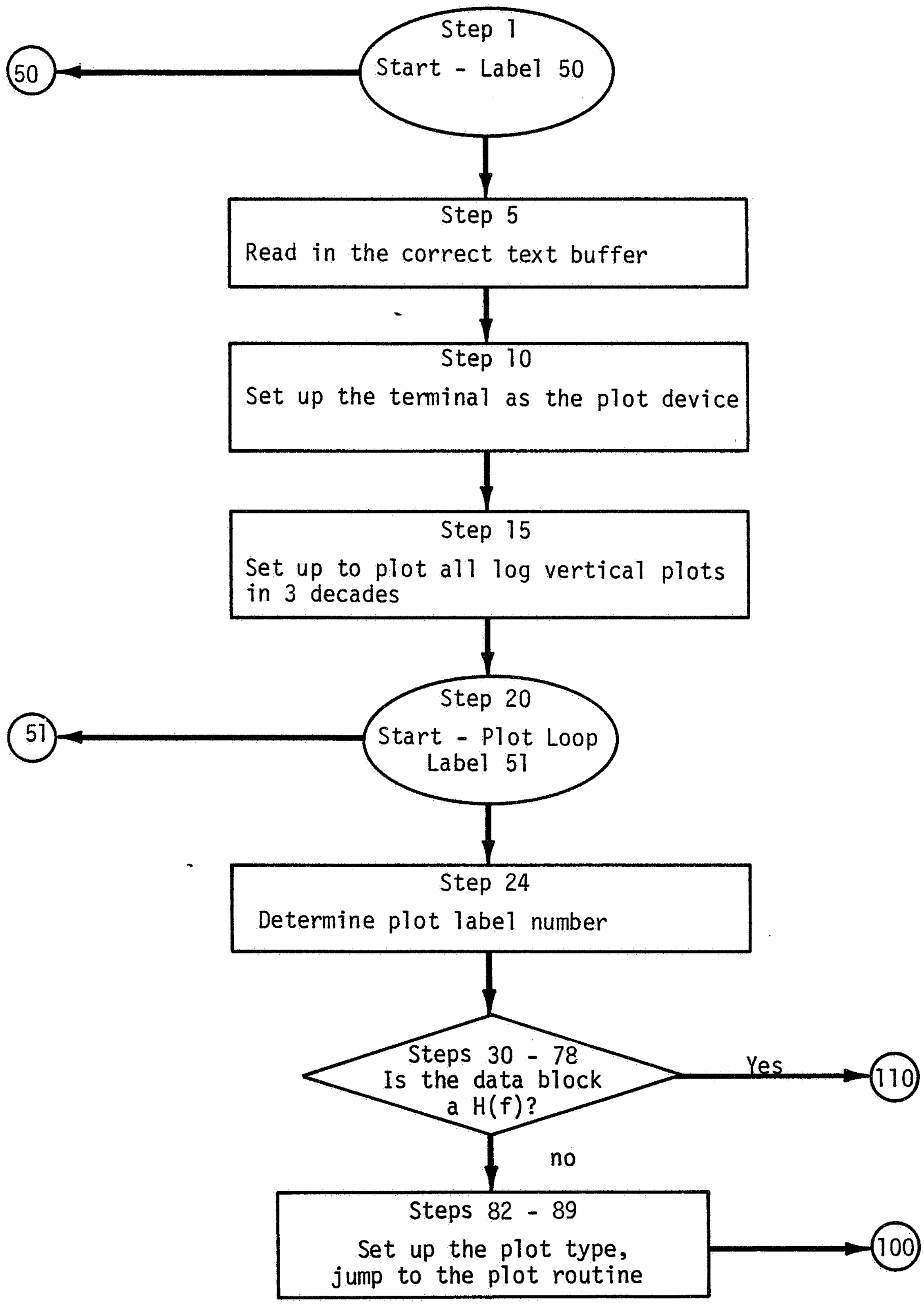
DIRECT POGO SOFTWARE FLOWCHART (Continued)



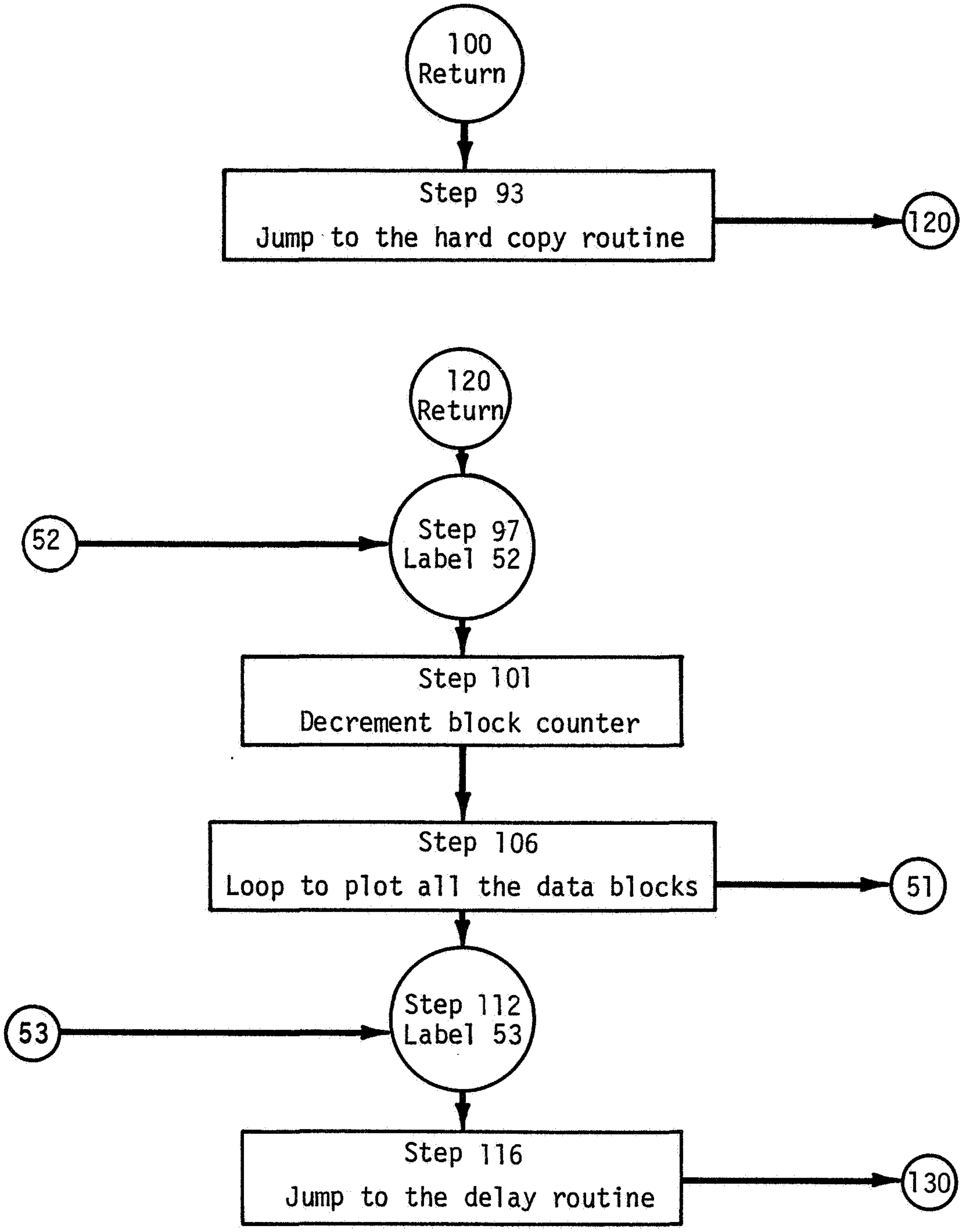
DIRECT POGO SOFTWARE FLOWCHART (Concluded)



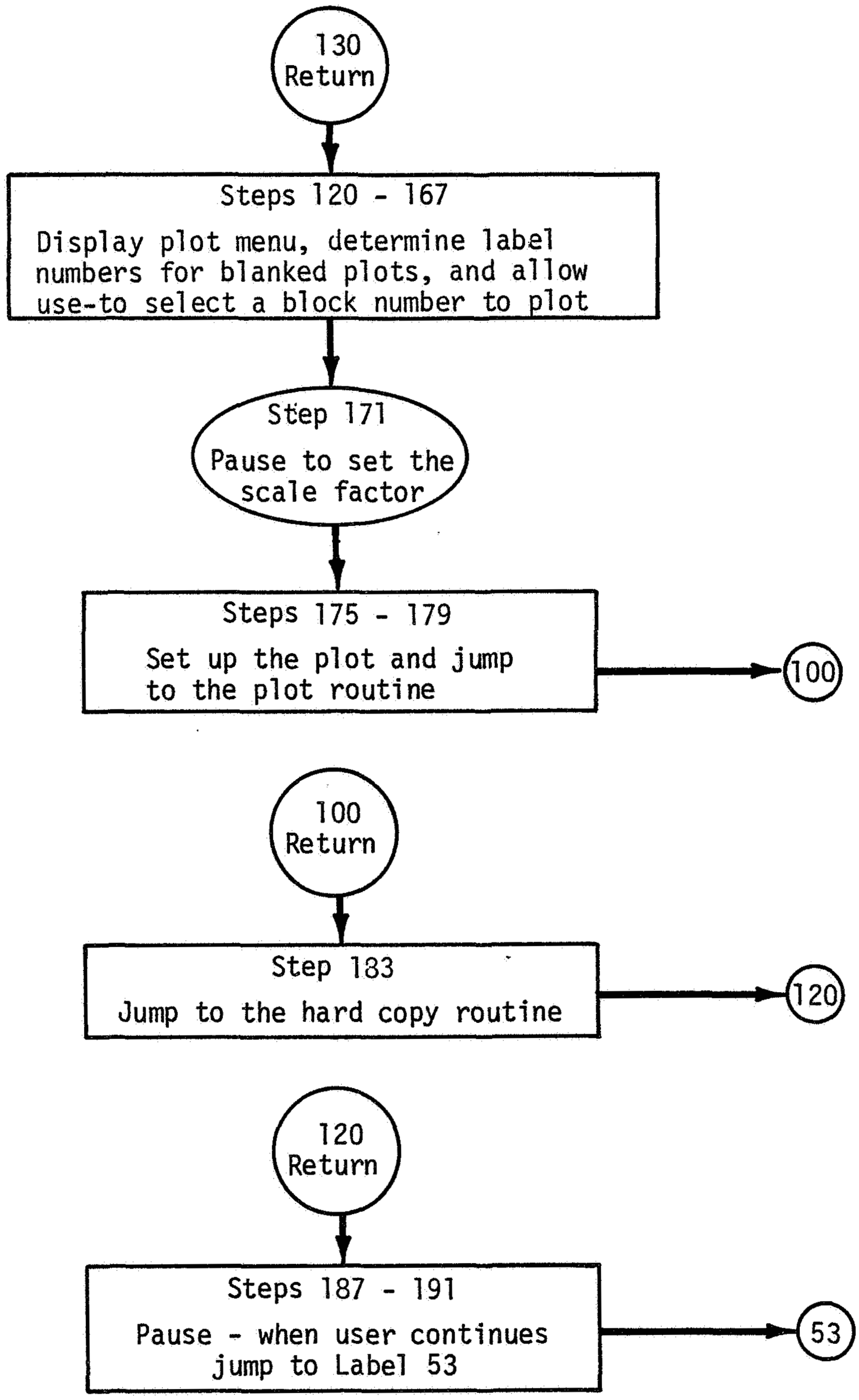
POGO SOFTWARE PLOT ROUTINE



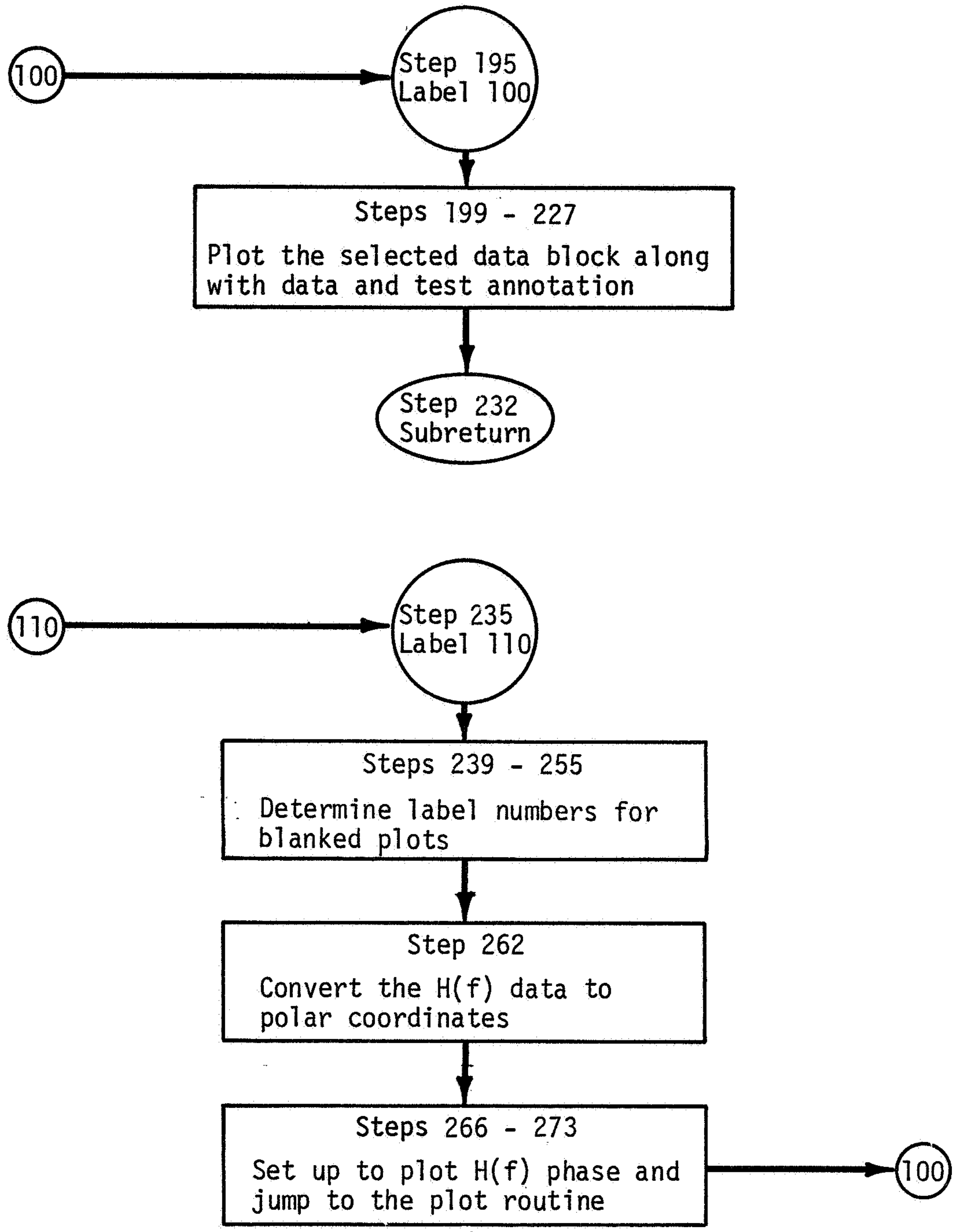
POGO SOFTWARE PLOT ROUTINE (Continued)



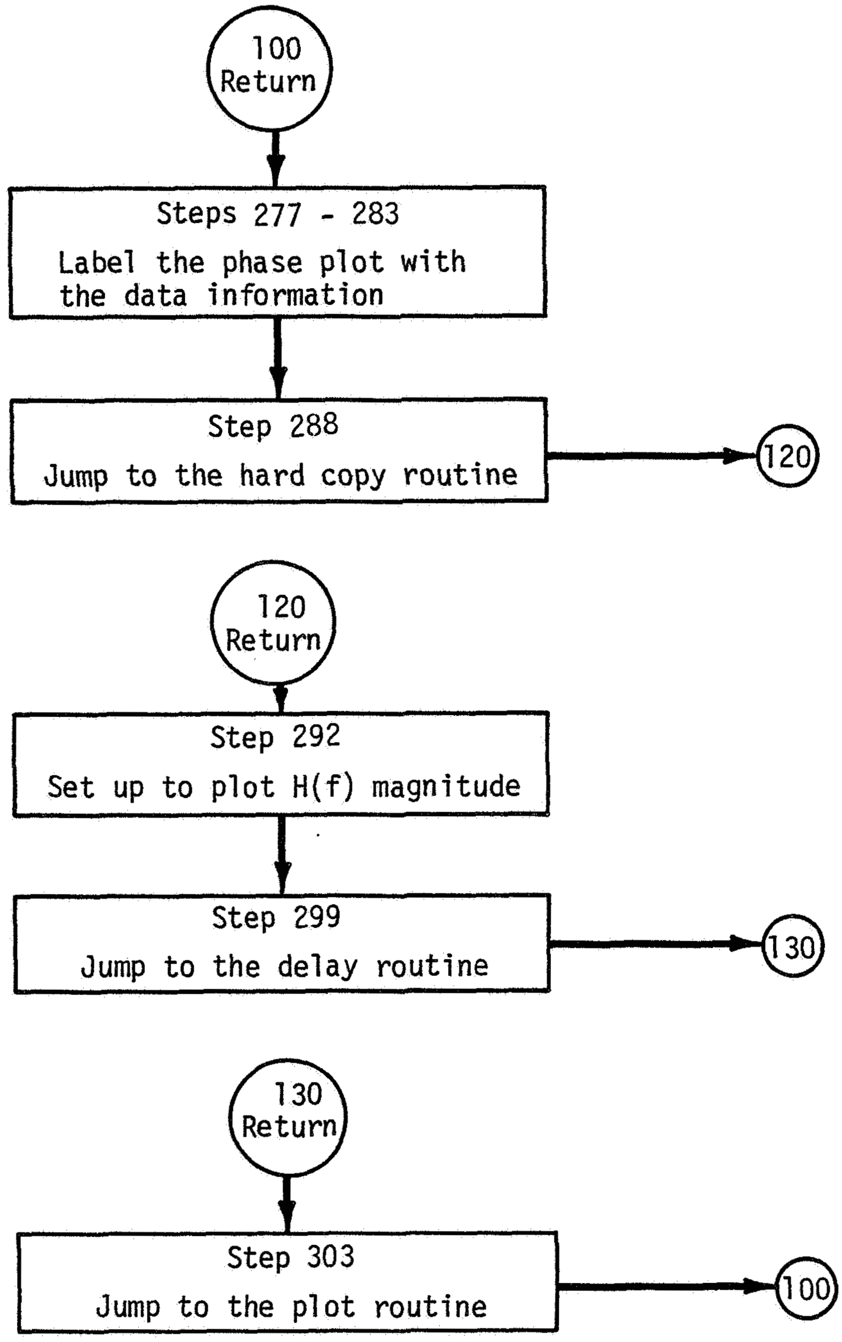
POGO SOFTWARE PLOT ROUTINE (Continued)



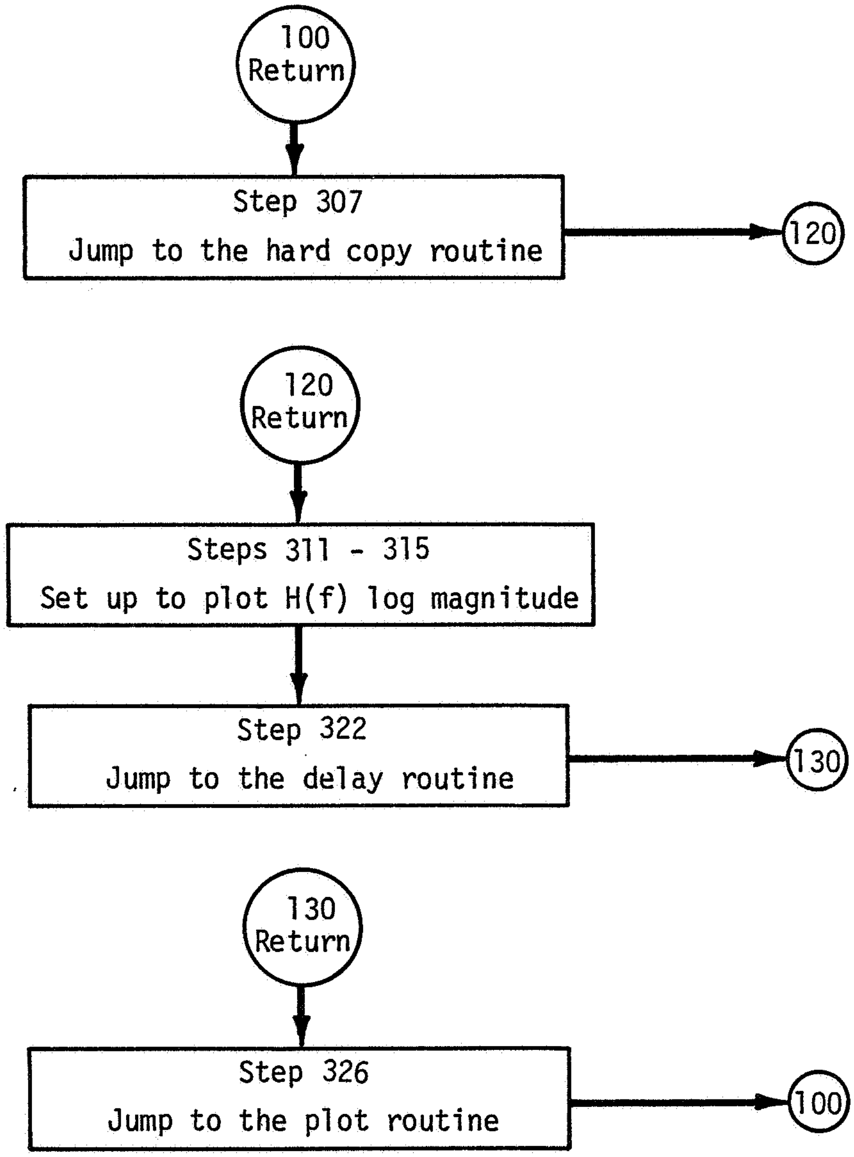
POGO SOFTWARE PLOT ROUTINE (Continued)



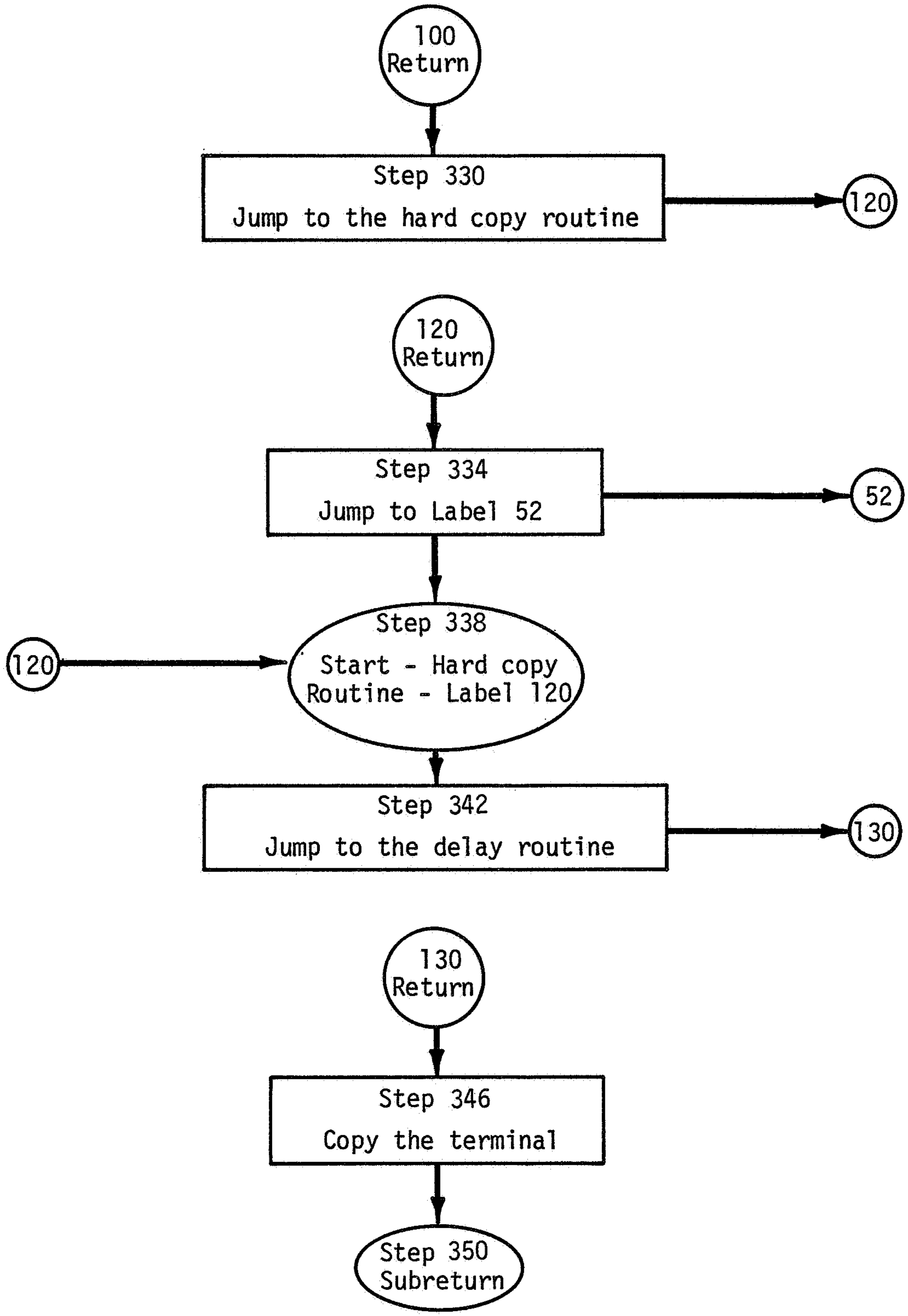
POGO SOFTWARE PLOT ROUTINE (Continued)



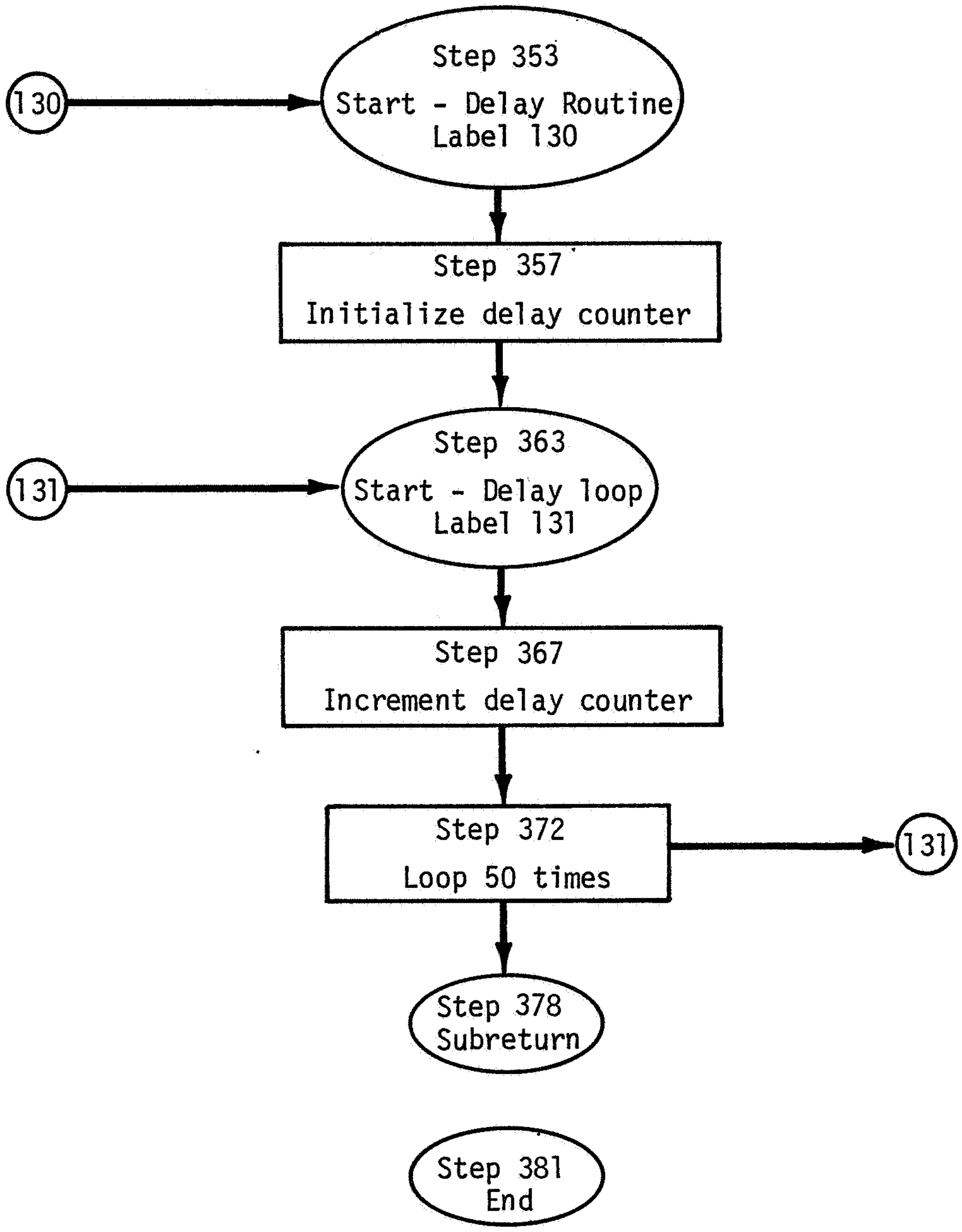
POGO SOFTWARE PLOT ROUTINE (Continued)



POGO SOFTWARE PLOT ROUTINE (Continued)



POGO SOFTWARE PLOT ROUTINE (Concluded)



APPENDIX B

POGO SOFTWARE LISTING

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APPENDIX B

POGO SOFTWARE LISTING

KEYBOARD FILE 1 - RATIO POGO SOFTWARE PART 1

1	L	0			Label 0
5	BS	4096			Set blocksize to 4096
9	CL				
12	CL	1			
16	CL	2			
20	CL	3			Clear blocks 0 through 6
24	CL	4			
28	CL	5			
32	CL	6			
36	Y	5814			Call user program 5414 (blank terminal screen)
40	MS	34			Set text record pointer to zero (default)
44	MS	14			Read next text record (message #1)
48	Y R	1			Input from terminal VP1† (blocksize)
53	BS	1D			Set blocksize to VP1
57	MS	14			Read next text record (message #2)
61	Y R	2000	2003		Input from terminal VP2000, VP2001, VP2002, and VP2003 (calibration factors)
67	Y *	2000	2000D	100	VP2000 = VP2000 * 100
74	Y *	2001	2001D	100	VP2001 = VP2001 * 100
81	Y *	2002	2002D	100	VP2002 = VP2002 * 100
88	Y *	2003	2003D	100	VP2003 = VP2003 * 100
95	MS	14			Read next text record (message #3)
99	Y R	2			Input from terminal VP2 (number of data acquisition loops)
104	MS	14			Read next text record (message #4)
108	Y R	2004			Input from terminal VP2004 (Δf)

†This means the variable of parameter 1.

KEYBOARD FILE 1 - RATIO POGO SOFTWARE PART 1 (Continued)

113 Y *	2004	2004D	10		VP2004 = VP2004 * 10
120 MS	34	20			Set text record pointer to 20
125 MS	14				Read next text record (message #7)
129 D					Display block 0 (used as program pause)
132 MS	32				Set ADC Throughput File pointer to 0
136 MS	22	4	2D		Write analog data to the ADC throughput file. No. of records = 2D (4 channels each)
142 L	10				Label 10
146 Y _	3	18			Set VP3 to 18
152 Y _	4	19			Set VP4 to 19
158 Y _	5	22			Set VP4 to 22
164 Y _	6	23			Set VP6 to 23
170 Y _	7	2			Set VP7 to 2
176 Y _	8	12			Set VP8 to 12
182 L	11				Label 11
186 CL					
189 CL	1				
193 CL	2				
197 CL	3				Clear blocks 0 through 6
201 CL	4				
205 CL	5				
209 CL	6				
213 Y _	9	3			Set VP9 to 3
219 Y A+	10	7D	1999		VP10 = VP7 + 1999
226 Y	41	0	0	0	Call user program 41; n1=0= center frequency of the band of interest, n2=0=width of the band of interest, n3=0=ADC throughput start record. (Initializes off-line BSFA)
233 L	12				Label 12
237 Y	45	2	0	7D	Call user program 45; n1=2=block number where the data will be stored, n2=0=number of Hannings applied to the data, n3=VP7= channel that will be read from the disc. (Off-line BSFA)

KEYBOARD FILE 1 - RATIO POGO SOFTWARE PART 1 (Continued)

244 Y	45	1	0	1	Call user program 45; n1=1, n2=0, n3=1
251 *	2	-10D			Multiply block 2 by VP(VP10)[†]
256 :	2	100			Divide block 2 by 100
261 *	1	2000D			Multiply block 1 by VP2000
266 :	1	100			Divide block 1 by 100
271 SP	1	2	2		Compute the average auto- and cross-power spectrums, where block n1=input data block and block n1+1=output, n2=2 specifies dual channel, n3=2 specifies double precision
277 #	12	2D	0		Loop through label 12 VP2 times
283 CH	1	2	2		Calculate transfer function data where n1=input data block, n2=2 specifies dual channel, n3=2 specifies double precision
289 X<	1				Load block 1 into block 0
293 X>	8D				Store block 0 into block VP8 [H(f)]
297 Y A+	8				VP8 = VP8 + 1
303 X<	2				Load block 2 into block 0
307 X>	8D				Store block 0 into VP8 [γ^2(f)]
311 L	13				Label 13
315 :	9D	2004D			Divide block VP9 by VP2004
320 *	9D	20			Multiply block VP9 by 20
325 X<	9D				Load block VP9 into block 0
329 X>	-9D				Store block 0 into block VP(VP9)
333 Y A+	9				VP9 = VP9 + 1
339 #	13	4	0		Loop through label 13 four times
345 Y A+	4				VP4 = VP4 + 1
351 Y A+	5	5D		2	VP5 = VP5 + 2
358 Y A+	6	6D		2	VP6 = VP6 + 2
365 Y A+	7				VP7 = VP7 + 1

[†]The minus sign in front of the VP number means to use the value in the VP that is specified by the value of the VP given (i.e., the value of the VP specified by VP10).

KEYBOARD FILE 1 - RATIO POGO SOFTWARE PART 1 (Concluded)

371 Y A+	8			VP8 = VP8 + 1
377 #	11	3	0	Loop through label 11 three times
383 J	20	2		Jump to label 20 in keyboard stack 2
388 .				End

KEYBOARD FILE 2 - RATIO POGO SOFTWARE PART 2

1	L	20			Label 20	
5	TR	12			Convert blocks 12	
9	TR	14			Convert blocks 14	to rectangular coordinates
13	TR	16			Convert blocks 16	
17	Y _	3	3		Set VP3 to 3	
23	Y _	4	6		Set VP4 to 6	
29	Y _	5	7		Set VP5 to 7	
35	Y _	6	14		Set VP6 to 14	
41	Y _	7	12		Set VP7 to 12	
47	Y _	8	16		Set VP8 to 16	
53	Y _	9	14		Set VP9 to 14	
59	Y _	10	16		Set VP10 to 16	
65	Y _	11	12		Set VP11 to 12	
71	Y _	12	13		Set VP12 to 13	
77	Y _	13	15		Set VP13 to 15	
83	Y :·	14	1D	2	VP14 = VP1/2	
90	Y A+	14			VP14 = VP14 + 1	
95	Y _	15	17		Set VP15 to 17	
101	Y _	17	13		Set VP17 to 13	
107	L	21			Label 21	
111	Y TR	21	-5D	0	Get the block qualifiers from block VP(VP5) and put them in VP21 - VP25	
118	Y TR	21	3D	1	Put the block qualifiers stored in VP21 - VP25 into block VP3	
125	Y TR	21	4D	1	Put the block qualifiers into block VP4	
132	Y TR	21	-12D	0	Get the block qualifiers from block VP(VP12) and put them into VP21 - VP25	
139	Y TR	21	5D	1	Put the block qualifiers into block VP5	
146	Y _	0	0		Set VP0 to 0	
152	L	22			Label 22	
156	Y X<	3000	-4D	0D	Get the complex data from block VP(VP4), channel VP0, and put the values into complex VP3000	

KEYBOARD FILE 2 - RATIO POGO SOFTWARE PART 2 (Continued)

163	Y	X<	3001	-5D	0D		Get the complex data from block VP(VP5), channel VP0 and put them into complex VP3001
170	Y	X<	2005	12D	0D		Get the real data from block VP12, channel VP0 and put it into VP2005
177	Y	X<	2006	-12D	0D		Get the real data from block VP(VP12), channel VP0 and put it into VP2006
184	Y	IF	2005	0	7	0	If VP2005 = 0, skip seven steps
192	Y	:	2005	1	2005D		VP2005 = 1/VP2005
199	Y	If	2006	0	5	0	If VP2006 = 0, skip five steps
207	Y	:	2006	1	2006D		VP2006 = 1/VP2006
214	Y	A+	2007	2005D	2006D		VP2007 = VP2005 + VP2006
221	Y	A-	2007				VP2007 = VP2007 - 1
226	Y	:	2007	1	2007D		VP2007 = 1/VP2007
233	Y	IF	2007	0	1	2	If VP2007 > 0, skip one step
241	Y	_	2007	0			Set VP2007 to 0
247	Y	X>	2007	5D	0D		Put VP2007 into the real part of block VP5, channel VP0
254	Y	*	2009	2900D	2902D		VP2009 = VP2900 * VP2902 (ac)
261	Y	*	2010	2901D	2903D		VP2010 = VP2901 * VP2903 (bd)
268	Y	*	2011	2901D	2902D		VP2011 = VP2901 * VP2902 (bc)
275	Y	*	2012	2900D	2903D		VP2012 = VP2900 * VP2903 (ad)
282	Y	*	2013	2902D	2902D		VP2013 = $(\text{VP2902})^2$ (c^2)
289	Y	*	2014	2903D	2903D		VP2014 = $(\text{VP2903})^2$ (d^2)
296	Y	A+	2015	2013D	2014D		VP2015 = VP2013 + VP2014 (c^2+d^2)
303	Y	A+	2016	2009D	2010D		VP2016 = VP2009 + VP2010 (ac+bd)
310	Y	A-	2017	2011D	2012D		VP2017 = VP2009 - VP2012 (bc-ad)
317	Y	:	2904	2016D	2015D		VP2904 = VP2016/VP2015 $\left[\frac{(ac+bd)}{(c^2+d^2)}\right]$
324	Y	:	2905	2017D	2015D		VP2905 = VP2017/VP2015 $i\left[\frac{(bc-ad)}{(c^2+d^2)}\right]$
331	Y	IF	2904	7	1	2	If VP2094 > 7, skip one step
339	Y	IF	2904	-7	1	1	If VP2904 ≥ -7, skip one step
347	Y	_	2904	0			Set VP2904 to 0

KEYBOARD FILE 2 - RATIO POGO SOFTWARE PART 2 (Concluded)

353	Y IF	2905	7	1	2	If VP2905 > 7, skip one step
361	Y IF	2905	-7	1	1	If VP2905 $\geq$ -7, skip one step
369	Y _	2905	0			Set VP2905 to 0
375	Y X>	3002	4D	0D		Put complex VP3002 into block VP4, channel VP0
382	Y A+	0				VP0 = VP0 + 1
387	#	22	14D	0		Loop through label 22 VP14 times
393	Y A+	3				VP3 = VP3 + 1
398	Y A+	4	4D	2		VP4 = VP4 + 2
405	Y A+	5	5D	2		VP5 = VP5 + 2
412	Y A+	12	12D	2		VP12 = VP12 + 2
419	#	21	3	0		Loop through label 21 three times
425	J	30	3			Jump to label 30, keyboard stack 3
430	.					End

KEYBOARD FILE 3 - RATIO POGO SOFTWARE PART 3

1	L	30					Label 30
5	Y _	31	7				Set VP31 to 7
11	Y _	35	6				Set VP35 to 6
17	Y _	36	3				Set VP36 to 3
23	J	32					Jump to label 32
27	L	31					Label 31
31	Y _	3	1				Set VP3 to 1
37	Y _	4	27				Set VP4 to 27
43	Y _	5	16				Set VP5 to 16
49	Y _	6	14				Set VP6 to 14
55	Y _	7	12				Set VP7 to 12
61	Y _	8	10				Set VP8 to 10
67	Y _	9	8				Set VP9 to 8
73	Y _	10	6				Set VP10 to 6
79	Y _	11	25				Set VP11 to 25
85	Y _	12	24				Set VP12 to 24
91	Y _	13	125				Set VP13 to 125
97	J	50	5				Jump to label 50 in Keyboard File 5
102	L	32					Label 32
106	MS	34	82				Set the text record pointer to 82
111	MS	14					Read next text record (type of blanking routine
115	Y R	30					Input from terminal VP30
120	Y IF	30	0	1	2		IF VP30>0, skip 1 step
128	Y A+	31	31D	11			VP31 = VP31 + 11
135	X<	31D					Load blanking block (VP31)
139	MS	14					Read the next text record (minimum blanking value)
143	Y R	2030					Input from terminal VP2030
148	Y :	39	10D	2			VP39 = VP1/2
155	Y A-	39					VP39 = VP39 - 1
160	L	33					Label 33
164	TR	35D					

KEYBOARD FILE 3 - RATIO POGO SOFTWARE PART 3 (Concluded)

168	CL	36D					Clear block BP36
172	Y TR	21	35D	0			Get the block qualifiers from block VP35 and put them into VP21 - VP25
179	Y TR	21	36D	1			Put the block qualifiers stored in VP21-VP25 into block VP36
186	Y _	32	0				Set VP32 to 0
192	Y _	33	1				Set VP33 to 1
198	Y _	34	2				Set VP34 to 2
204	L	34					Label 34
208	Y _	3000	0				Set VP3000 to 0
214	Y X<	2032	31D	32D			Get the real data from block VP31, channel VP32 and store it in VP2032
221	Y X<	2033	31D	33D			Get the real data from block BP31, channel VP33 and store it in VP2033
228	Y X<	2034	31D	34D			Get the real data from block VP31, channel VP34 and store it in VP2034
235	Y IF	2033	2030D	3	-2		If VP2033<VP2030, skip 3 steps
243	Y IF	2033	2032D	2	-2		If VP2033<VP2032, skip 2 steps
251	Y IF	2033	2034D	1	-2		If VP2033<VP2034, skip 1 step
259	Y X<	3000	35D	33D			Get the complex data from block VP35, channel VP33 and store it in VP3000
266	Y X>	3000	36D	33D			Put the complex data stored in VP3000 into block VP36, channel VP33
273	Y A+	32					VP32 = VP32 + 1
278	Y A+	33					VP33 = VP33 + 1
283	Y A+	34					VP34 = VP34 + 1
288	#	34	39D				Loop through label 34 VP39 times
294	Y A+	35	35D	2			VP35 = VP35 + 2
301	Y A+	36					VP36 = VP36 + 1
306	Y A+	31	31D	30D			VP31 = VP31 + VP30
313	#	33	3				Loop through label 33 three times
319	<						Subreturn
322.							End

KEYBOARD FILE 4 - DIRECT POGO SOFTWARE

1	L	40				Label 40
5	X<	18				Load block 18 into block 0
9	X>	20				Store block 0 into block 20
13	Y _	3	8			Set VP3 to 8
19	Y _	4	14			Set VP4 to 14
25	Y _	8	3			Set VP8 to 3
31	Y _	10	4			Set VP10 to 4
37	Y _	12	4			Set VP12 to 4
43	Y _	14	2			Set VP14 to 2
49	Y _	16	3			Set VP16 to 3
55	Y _	18	2			Set VP18 to 2
61	L	41				Label 41
65	CL					
68	CL	1				
72	CL	2				
76	CL	3				Clear blocks 0 through 6
80	CL	4				
84	CL	5				
88	CL	6				
92	Y	41	0	0	0	Call User Program 41, where n1=n2=n3=0 (Initialize off-line BSFA)
99	Y A+	5	-4D	1999		VP5 = 1999 + VP(VP4)
106	Y A+	7	-3D	1999		VP7 = 1999 + VP(VP3)
113	L	42				Label 42
117	Y	45	2	0	-3D	Call User Program 45; n1=2, n2=0, n3=VP(VP3) (off-line BSFA)
124	Y	45	1	0	-4D	Call User Program 45; n1=1, n2=0, n3=VP(VP4)
131	*	2	-7D			Multiply block 2 by VP(VP7)
136	:	2	100			Divide block 2 by 100
141	*	1	-5D			Multiply block 1 by VP(VP5)
146	:	1	100			Divide block 1 by 100
151	SP	1	2	2		Calculate averaged 2-channel-double precision power spectrum

KEYBOARD FILE 4 - DIRECT POGO SOFTWARE (Continued)

157	#	42	2D	0	Loop through label 42 VP2 times
163	CH	1	2	2	Calculate H(f) and γ^2(f) from the averaged power spectrum data
169	X<	1			Load block 1 into block 0 [H(f)]
173	X>	3D			Store block 0 into block VP3
177	Y A+	3			VP3 = VP3 + 1
183	X<	2			Load block 2 into block 0 [γ^2(f)]
187	X>	3D			Store block 0 in block VP3
191	:	5	2004D		Divide block 5 by VP2004
196	*	5	20		Multiply block 5 by 20
201	:	6	2004D		Divide block 6 by VP2004
206	*	6	20		Multiply block 6 by 20
211	X<	5			Load block 5 into block 0
215	X>	4D			Store block 0 in block VP4
219	Y A+	4			VP4 = VP4 + 1
225	X<	6			Load block 6 into block 0
229	X>	4D			Store block 0 into block VP4
233	Y A+	3			VP3 = VP3 + 1
239	Y A+	4			VP4 = VP4 + 1
245	#	41	3	0	Loop through label 41 three times
251	L	43			Label 43
255	Y _	31	9		Set VP31 to 9
261	Y _	35	8		Set VP35 to 8
267	Y _	36	5		Set VP36 to 5
273	J	32	3		Jump to label 33 in Keyboard File 3
278	L	44			Label 44
282	Y _	3	2		Set VP3 to 2
288	Y _	4	19		Set VP4 to 19
294	Y _	5	12		Set VP5 to 12
300	Y _	6	10		Set VP6 to 10
306	Y _	7	8		Set VP7 to 8
312	Y _	8	8		Set VP8 to 8
318	Y _	9	8		Set VP9 to 8

KEYBOARD FILE 4 - DIRECT POGO SOFTWARE (Concluded)

324	Y _	10	8	Set VP10 to 8
330	Y _	11	15	Set VP11 to 15
336	Y _	12	58	Set VP12 to 58
342	Y _	13	150	Set VP13 to 150
348	J	50	5	Jump to lable 50 in Keyboard File 5 (Plot Routine)
353	.			End

KEYBOARD FILE 5 - POGO PLOT ROUTINE

1	L	50				Label 50
5	Y	5838	3D			Call User Program 5838; n1=VP3 (Read text buffer VP3 into core)
10	Y	5821	6			Call User Program 5821; n1=6 (Set up the terminal as the plot device)
15	Y	5865	3			Call User Program 5865; n1=3 (Set log plots to plot 3 decades, vertical scale)
20	L	51				Label 51
24	Y _	26	4D			Set VP26 to the value of VP4
30	Y IF	4	5D	5	0	If VP4 = VP5, skip five steps
38	Y IF	4	6D	4	0	If VP4 = VP6, skip four steps
46	Y IF	4	7D	3	0	If VP4 = VP7, skip three steps
54	Y IF	4	8D	2	0	If VP4 = VP8, skip two steps
62	Y IF	4	9D	1	0	If VP4 = VP9, skip one step
70	Y IF	4	10D	1	2	If VP4 > VP10, skip one step
78	J	110				Jump to label 110
82	Y	5809	0	0	0	Call User Program 5809; n1=0, n2=0, n3=0 (Set up to plot real/magnitude, linear horizontal scale, scale switch at 12 o'clock)
89	J	100				Jump to label 100
93	J	120				Jump to label 120
97	L	52				Label 52
101	Y A-	4				VP4 = VP4 - 1
106	#	51	11D	0		Loop through label 51 VP11 times
112	L	53				Label 53
116	J	130				Jump to label 130
120	Y	5814				Call User Program 5814 (Blank the terminal screen)
124	MS	34	12D			Set the text record pointer to VP12
129	MS	14				Read the next message (plot menu)
133	Y R	4				Input VP4 (data block number to be plotted

KEYBOARD FILE 5 - POGO PLOT ROUTINE (Continued)

138 Y _	26	4D			Set VP26 to the value of VP4
144 Y IF	4	10D	2	1	If VP4 ≥ VP10, skip 2 steps
152 Y IF	30	0	1	0	If VP30 = 0, skip 1 step
160 Y A+	26	26D	30		VP26 = VP26 + 30
167 MS	14				Read the next message (Set the scale and press "CONTINUE")
171 D	4D				Display block VP4
175 Y	5809				Call User Program 5809; n1=n2= n3=default (Set up the plot according to the display switches)
179 J	100				Jump to label 100
183 J	120				Jump to label 120
187 D	4D				Display block VP4
191 J	53				Jump to label 53
195 L	100				Label 100
199 Y	5814				Call User Program 5814
203 Y	5829				Call User Program 5829 (Plot the full data block)
207 Y	5815	4D			Call User Program 5815; n1=VP4 (Plot the data from block VP4)
212 Y	5816				Call User Program 5816 (Plot the defaulted axis)
216 Y	5817	26D			Call User Program 5817; n1=VP26 (Label the vertical axis with text buffer message VP4 and the horizontal axis with the default label)
221 Y	5808	975	600		Call User Program 5808; n1=970, n2=600 (Position the cursor to y=97.0% of the vertical plot window and x=60.0% of the horizontal plot window)
227 Y	5819	1			Write text buffer message #1
232 <					Subreturn
235 L	110				Label 110
239 Y IF	4	10D	2	1	If VP4 ≥ VP10, skip 2 steps
247 Y IF	30	0	1	0	If VP30 = 0, skip 1 step

255	Y A+	26	26D	30		VP26 = VP26 + 30
262	TP	4D				Convert block VP4 to polar coordinates
266	Y	5809	1	0	0	Call User Program 5809; n1=1, n2=0, n3=0 (Set up to plot imaginary/phase, linear horizontal, scale switch to 12 o'clock)
273	J	100				Jump to label 100
277	Y	5808	970	13D		Call User Program 5808; n1=970, n2=VP13
283	Y	5819	26D			Call User Program 5819; n1=VP26
288	J	120				Jump to label 120
292	Y	5809	0	0	0	Call User Program 5809; n1=0, n2=0, n3=0
299	J	130				Jump to label 130
303	J	100				Jump to label 100
307	J	120				Jump to label 120
311	TL	4D				Convert block VP4 to log polar coordinates
315	Y	5809	0	0	0	Call User Program 5809; n1=0, n2=0, n3=0
322	J	130				Jump to label 130
326	J	100				Jump to label 100
330	J	120				Jump to label 120
334	J	52				Jump to label 52
338	L	120				Label 120
342	J	130				Jump to label 130
346	Y	5820				Call User Program 5820 (Hard copy the terminal)
350	<					Subreturn
353	L	130				Label 130
357	Y _	19	1			Set VP19 to 1
363	L	131				Label 131
367	Y A+	19				VP19 = VP19 + 1
372	#	131	50	0		Loop through label 131 fifty times
378	<					Subreturn
381	.					End

APPENDIX C

POGO SOFTWARE TEXT RECORDS (FILE 4a)

APPENDIX C

POGO SOFTWARE TEXT RECORDS (FILE 4a)

Line #	Contents
	Message #1
0	
1	This is a 5451C program, written for POGO data analysis. The program
2	reads 4 analog channels simultaneously and writes them directly to the
3	disc via the ADC Throughput. The time domain data is then called from
4	the disc and H(f)s calculated re. Pulser. H(f)s across devices are
5	calculated by ratios. 28 JANUARY 80
6	
7	Setup the ADC for the desired frequency resolution (Delta f), and
8	input signal-to-noise ratio. Then, enter Blocksize. (INTEGER LE 1024)
9	/*
	Message #2
10	Enter a calibration factor for each channel. (4 - FLOATING POINT)
11	/*
	Message #3
12	Enter the number of data acquisition loops. (INTEGER)
13	/*
	Message #4
14	Enter Delta f as specified by the ADC. (FLOATING POINT)
15	/*
	Message #7
20	Start the data tape. Press "CONTINUE."
21	/*

C2

Line # Contents

Message #8

RATIO POGO DATA PLOT MENU

```
The program output is located in core memory as follows:

  BLOCK#          DATA

      3    Weighted H(f) HPOP/LPOP
      4    Weighted H(f) MCC/HPOP
      5    Weighted H(f) MCC/LPOP
      6    H(f)    HPOP/LPOP
      7    Coh(f)      "
      8    H(f)    MCC/HPOP
      9    Coh(f)     "
     10    H(f)    MCC/LPOP
     11    Coh(f)     "
     12    H(f)    LPOP/Pulser
     13    Coh(f)      "
     14    H(f)    HPOP/Pulser
     15    Coh(f)      "
     16    H(f)    MCC/Pulser
     17    Coh(f)     "
     18    PSD     Pulser
     19    PSD     LPOP
     20    PSD     HPOP
     21    PSD     MCC
     22    Re XPSD LPOP/Pulser
     23    Im XPSD     "
     24    Re XPSD HPOP/Pulser
     25    Im XPSD     "
     26    Re XPSD MCC/Pulser
     27    Im XPSD    "

Please enter the Block# you wish to plot.
/*
```

Message #9

```
Set the scale and press "CONTINUE."
/*
```

Line # Contents

Message #10

DIRECT POGO DATA PLOT MENU

```
The program output is located in core as follows:

    BLOCK#          DATA

         5    Weighted H(f) HPOP/LPOP
         6    Weighted H(f) MCC/HPOP
         7    Weighted H(f) MCC/LPOP
         8    H(f)      HPOP/LPOP
         9    Coh(f)        "
        10    H(f)      MCC/HPOP
        11    Coh(f)        "
        12    H(f)      MCC/LPOP
        13    Coh(f)        "
        14    Re XPSD HPOP/LPOP
        15    Im XPSD       "
        16    Re XPSD MCC/HPOP
        17    Im XPSD       "
        18    Re XPSD MCC/LPOP
        19    Im XPSD       "

Please enter the block # you wish to plot.
/*
```

Message #11

```
Set the scale and press "CONTINUE".
/*
```

Message #12

```
Do you want:  Coherence blanking (enter 2)
              Pulser blanking (enter 0)?
/*
```

Message #13

```
Enter the minimum blanking value (floating point).
/*
```

APPENDIX D

POGO SOFTWARE TEXT BUFFERS (FILE 4b)

APPENDIX D

POGO SOFTWARE TEXT BUFFERS (FILE 4b)

Text Buffer #1

RATIO POGO PLOT LABELS

```
01
(TEST ID)
/*

13
  HPOP/LPOP Ratio H(f)
  Pulser Blanked
/*

04
  MCC/HPOP Ratio H(f)
  Pulser Blanked
/*

05
  MCC/LPOP Ratio H(f)
  Pulser Blanked
/*

06
  HPOP/LPOP Ratio H(f) - Polar
/*

07
  HPOP/LPOP Ratio Coh(f)
/*

08
  MCC/HPOP Ratio H(f) - Polar
/*

09
  MCC/HPOP Ratio Coh(f)
/*

10
  MCC/LPOP Ratio H(f) - Polar
/*

11
  MCC/LPOP Ratio Coh(f)
/*
```

D2

Text Buffer #1 (Continued)

```
12
 LPOP/Pulser H(f) - Polar
/*

13
 LPOP/Pulser Coh(f)
/*

14
 HPOP/Pulser H(f) - Polar
/*

15
 HPOP/Pulser Coh(f)
/*

16
 MCC/Pulser H(f) - Polar
/*

17
 MCC/Pulser Coh(f)
/*

18
 Pulser PSD
/*

19
 LPOP PSD
/*

20
 HPOP PSD
/*

21
 MCC PSD
/*

22
 LPOP/Pulser Real XPSD
/*

23
 LPOP/Pulser Imag XPSD
/*

24
 HPOP/Pulser Real XPSD
/*
```

Text Buffer #1 (Concluded)

```
25
  HPOP/Pulser Imag XPSD
/*

26
  MCC/Pulser Real XPSD
/*

27
  MCC/Pulser Imag XPSD
/*

33
  HPOP/LPOP Ratio H(f)
  Coherence Blanked
/*

34
  MCC/HPOP Ratio H(f)
  Coherence Blanked
/*

35
  MCC/LPOP Ratio H(f)
  Coherence Blanked
/*
```

Text Buffer #2

DIRECT POGO PLOT LABELS

```
01
(TEST ID)
/*

05
  HPOP/LPOP Direct H(f)
  Pulser Blanked
/*

06
  MCC/HPOP Direct H(f)
  Pulser Blanked
/*

07
  MCC/LPOP Direct H(f)
  Pulser Blanked
/*
```

Text Buffer #2 (Continued)

08
HPOP/LPOP Direct H(f) - Polar
/*

09
HPOP/LPOP Direct Coh(f)
/*

10
MCC/HPOP Direct H(f) - Polar
/*

11
MCC/HPOP Direct Coh(f)
/*

12
MCC/LPOP Direct H(f) - Polar
/*

13
MCC/LPOP Direct Coh(f)
/*

14
HPOP/LPOP Direct Real XPSD
/*

15
HPOP/LPOP Direct Imag XPSD
/*

16
MCC/HPOP Direct Real XPSD
/*

17
MCC/HPOP Direct Imag XPSD
/*

18
MCC/LPOP Direct Real XPSD
/*

19
MCC/LPOP Direct Imag XPSD
/*

35
HPOP/LPOP Direct H(f)
Coherence Blanked
/*

Text Buffer #2 (Concluded)

```
36
  MCC/HPOP Direct H(f)
  Coherence Blanked
/*

37
  MCC/LPOP Direct H(f)
  Coherence Blanked
/*
```

APPENDIX E

POGO SOFTWARE SAMPLE OUTPUT

```
**********************************************************************
This is a 5451C program, written for POGO data analysis.  The program
reads 4 analog channels simultaneously and writes them directly to the
disc via the ADC Throughput.  The time domain data is then called from
the disc and H(f)s calculated re. Pulser.  H(f)s across devices are
calculated by ratios.                                    28 JANUARY 80
**********************************************************************
Setup the ADC for the desired frequency resolution (Delta f), and
input signal-to-noise ratio.  Then, enter Blocksize. (INTEGER LE 1024)
512

Enter a calibration factor for each channel.  (4 - FLOATING POINT)
12.4 16.36 22.6 16.03

Enter the number of data acquisition loops.  (INTEGER)
22

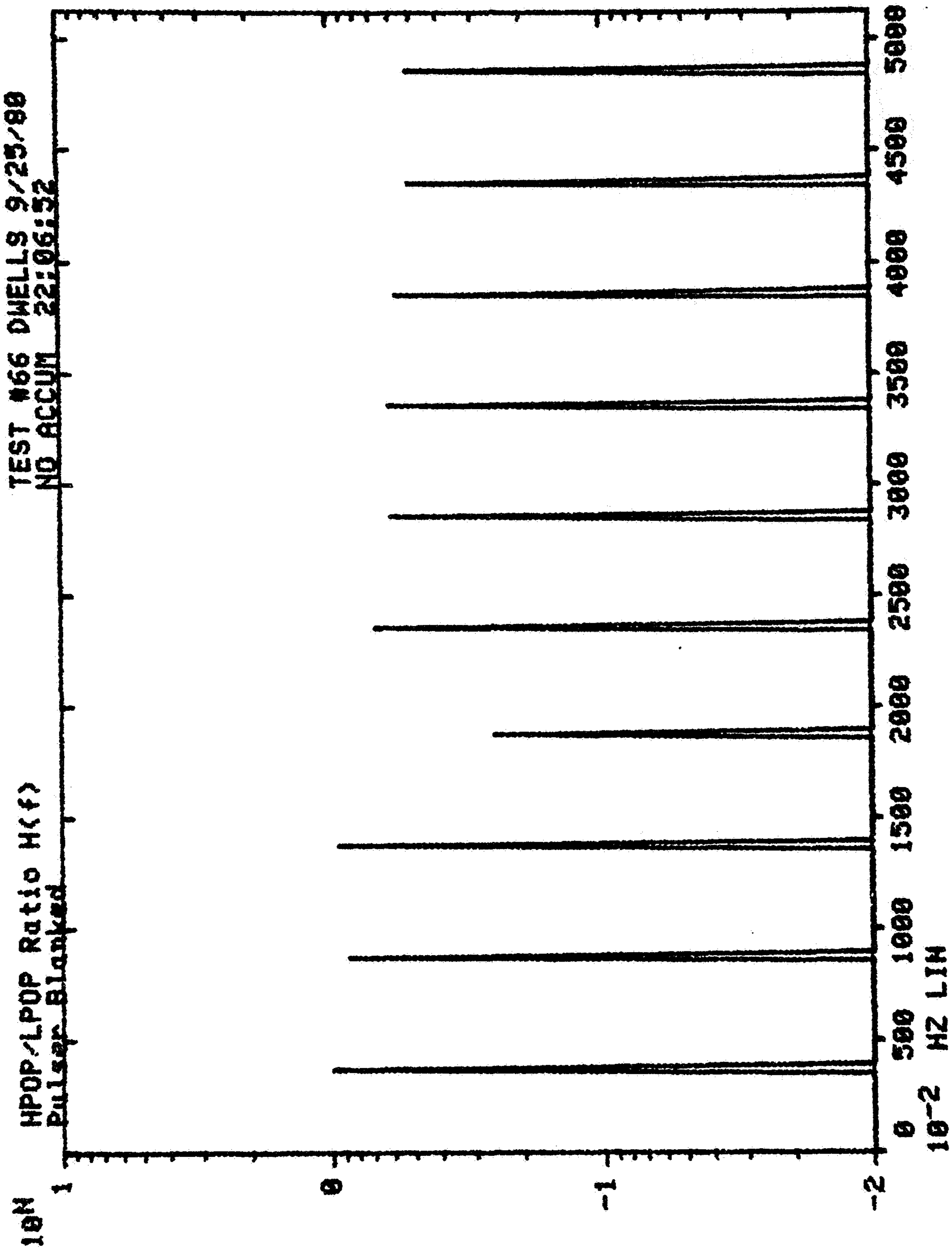
Enter Delta f as specified by the ADC.  (FLOATING POINT)
0.2


Start the data tape.  Press "CONTINUE".

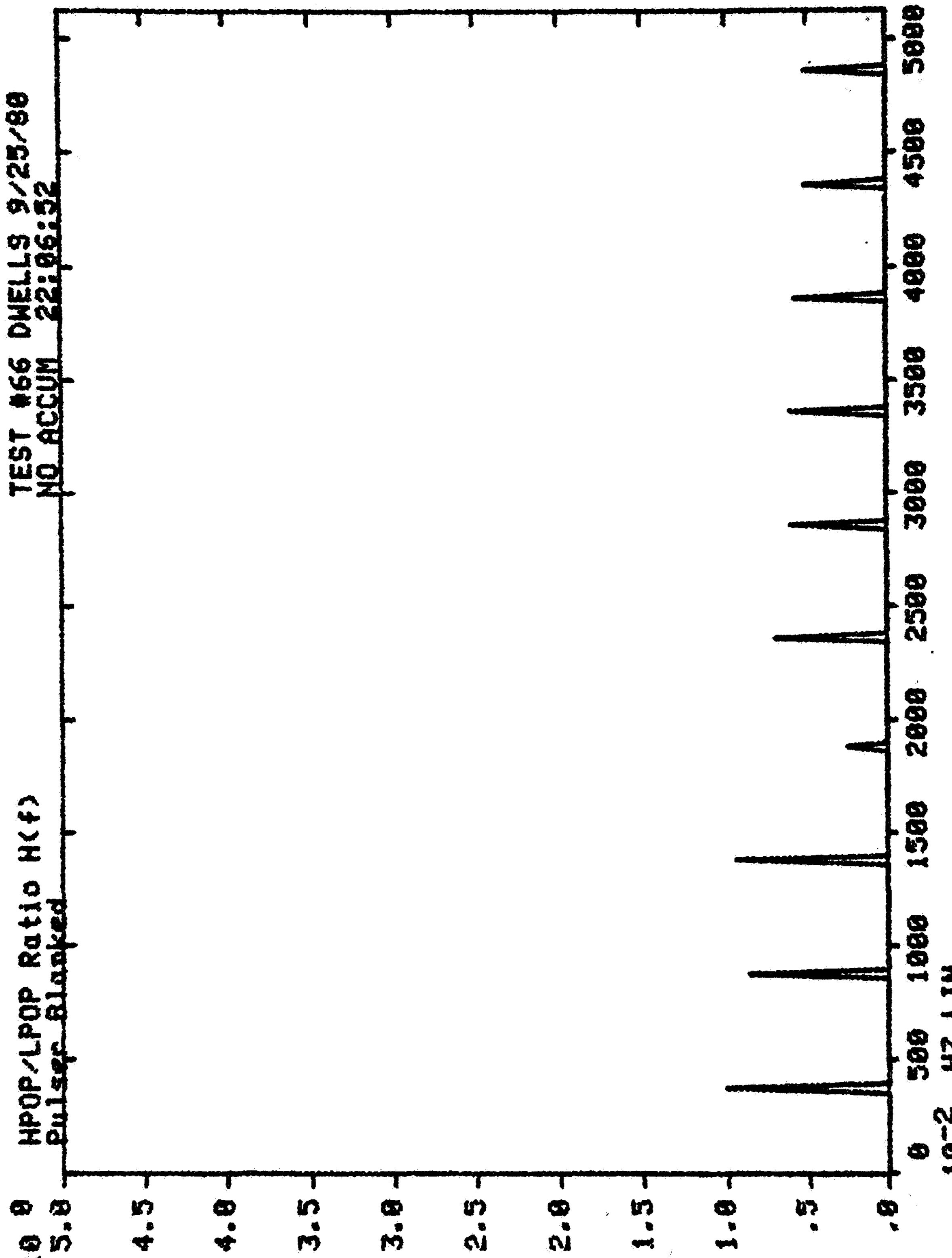

Do you want:  Coherence blanking (enter 2)
              Pulser Blanking    (enter 0) ?
0


Enter the minimum blanking value. (Floating Point)
0.0037
```

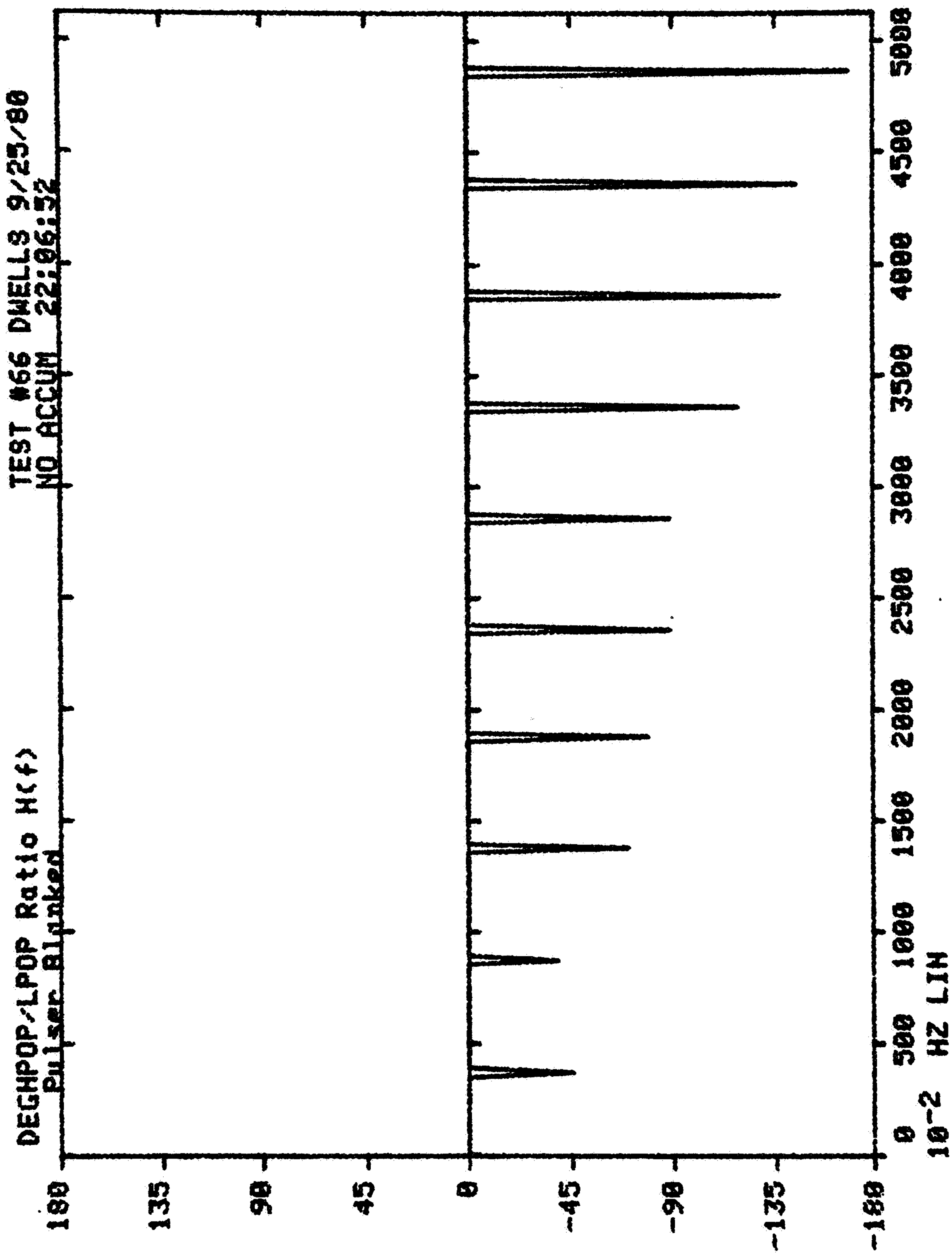
E2

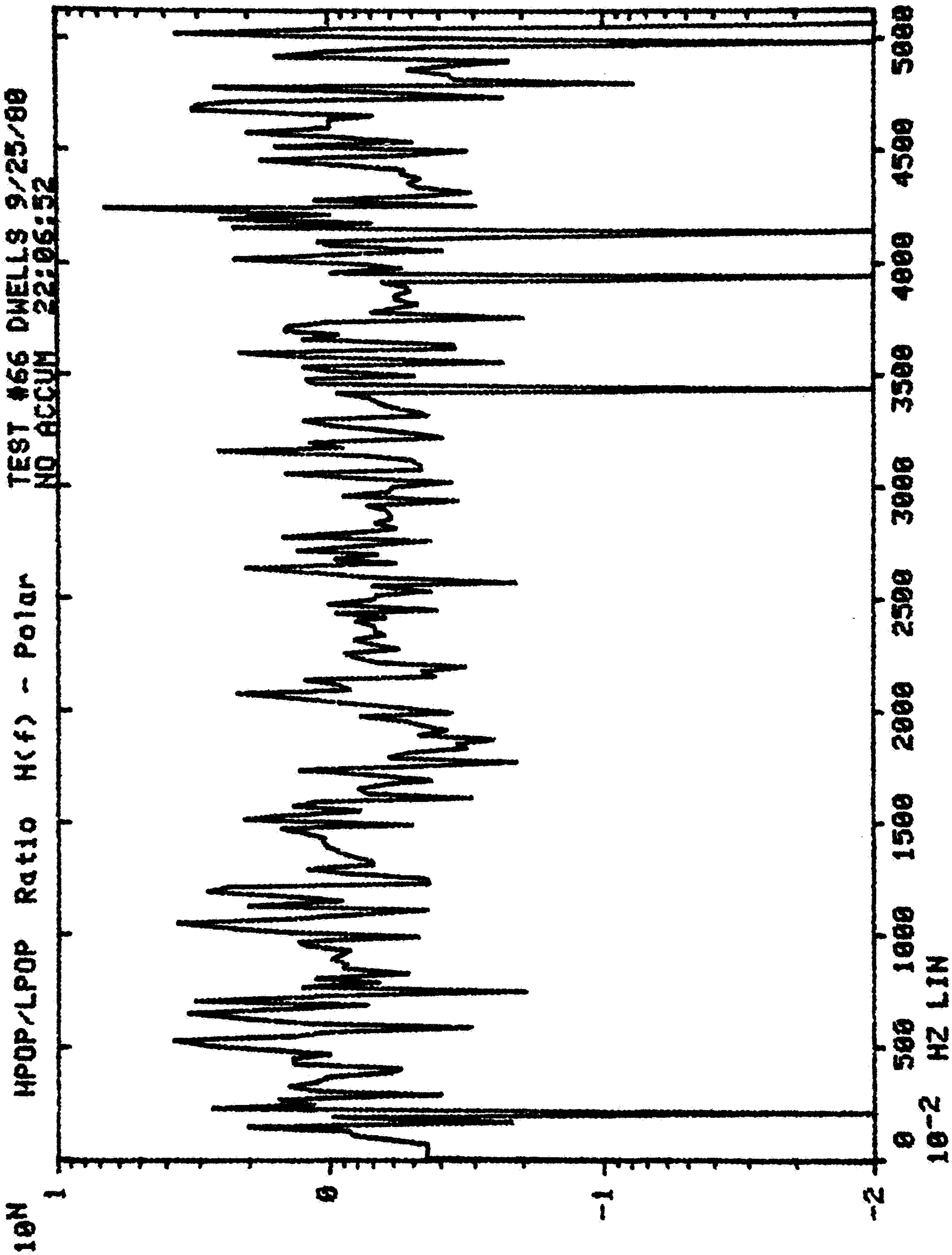

HPOP/LPOP Ratio H(f)
Pulsar Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
HZ LIN
10-2

E3

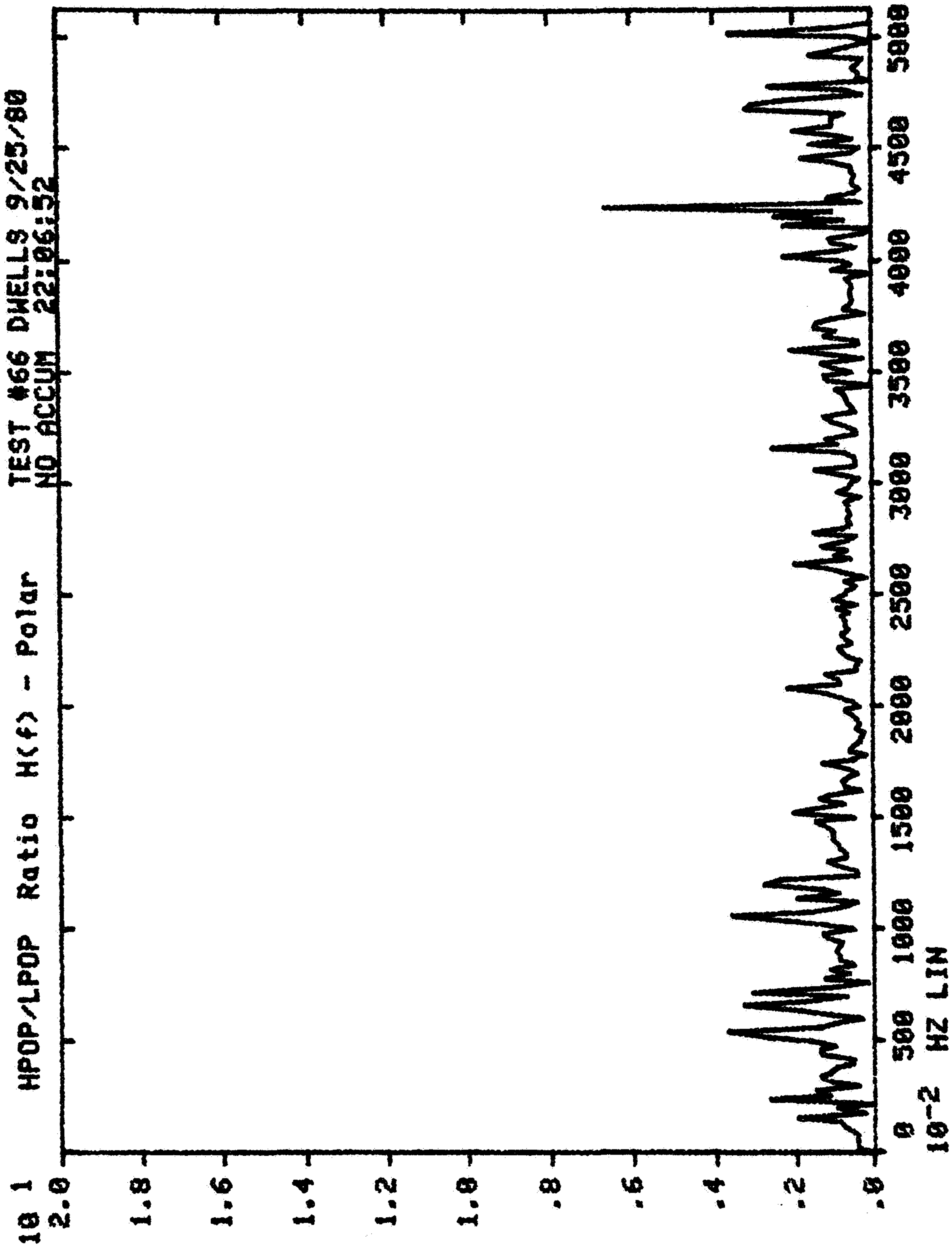

HPOP/LPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2
HZ LIN

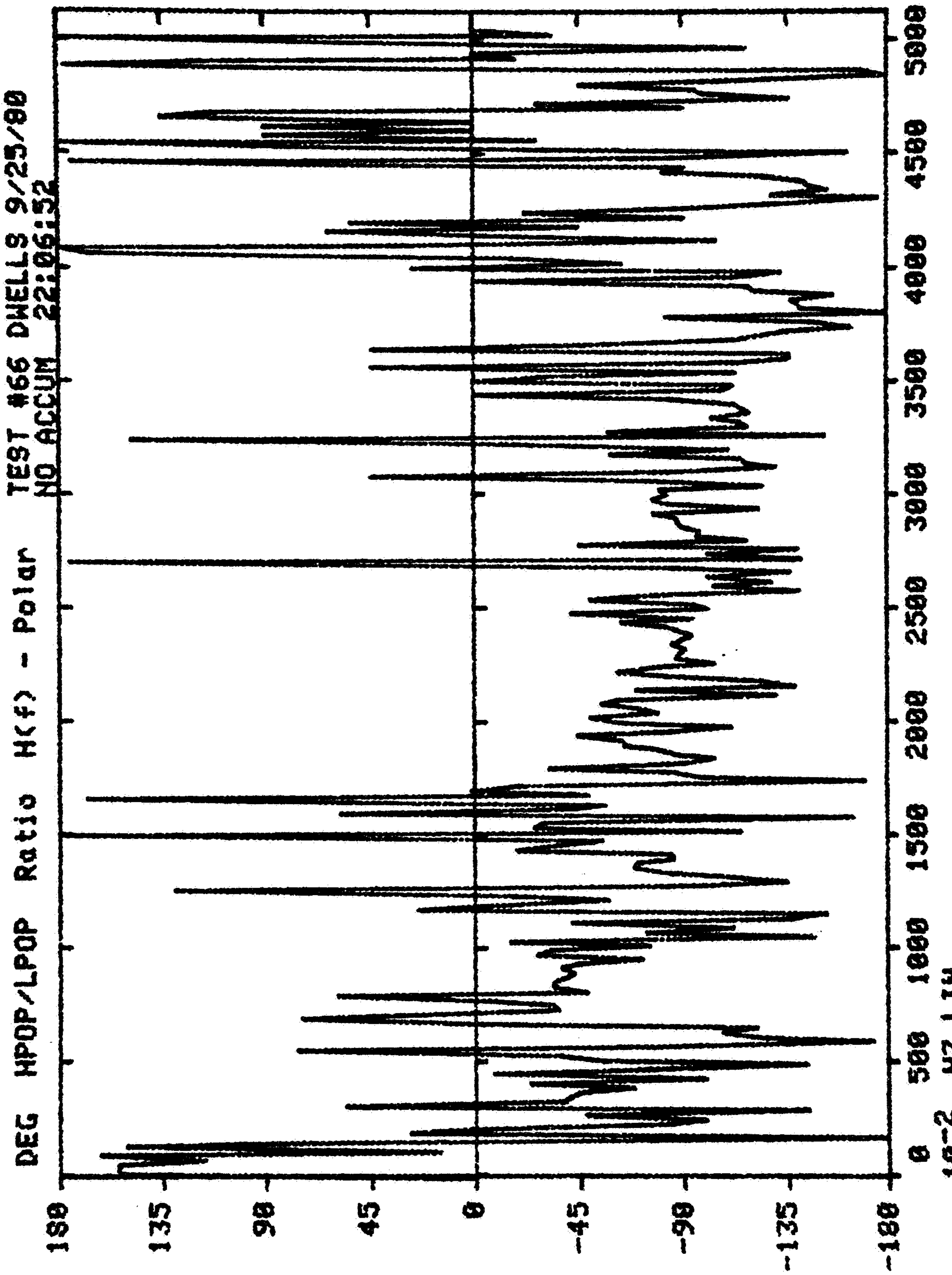
E4


DEGHPOP/LPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

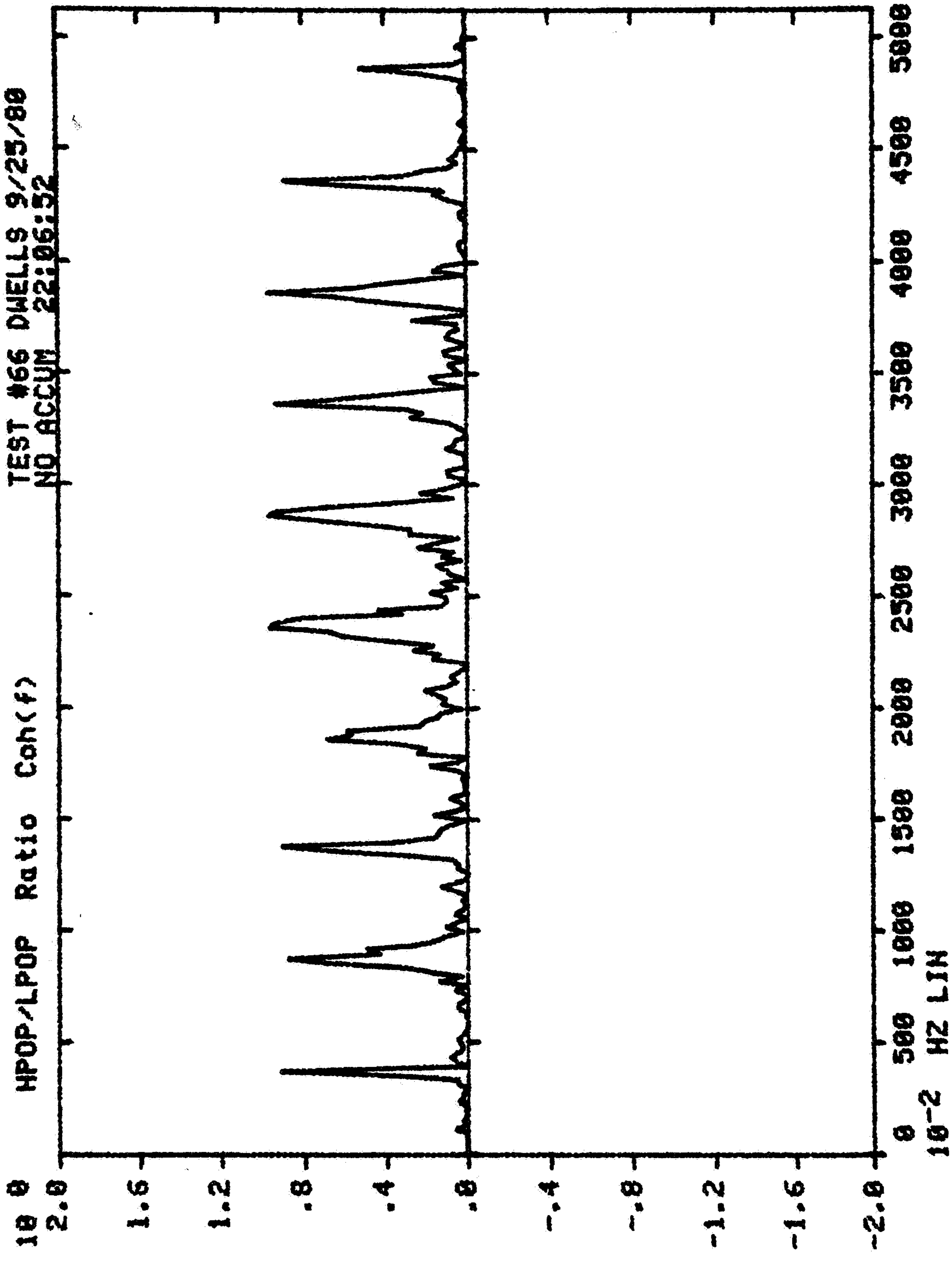

HPOP/LPOP Ratio H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E6


HPOP/LPOP Ratio H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

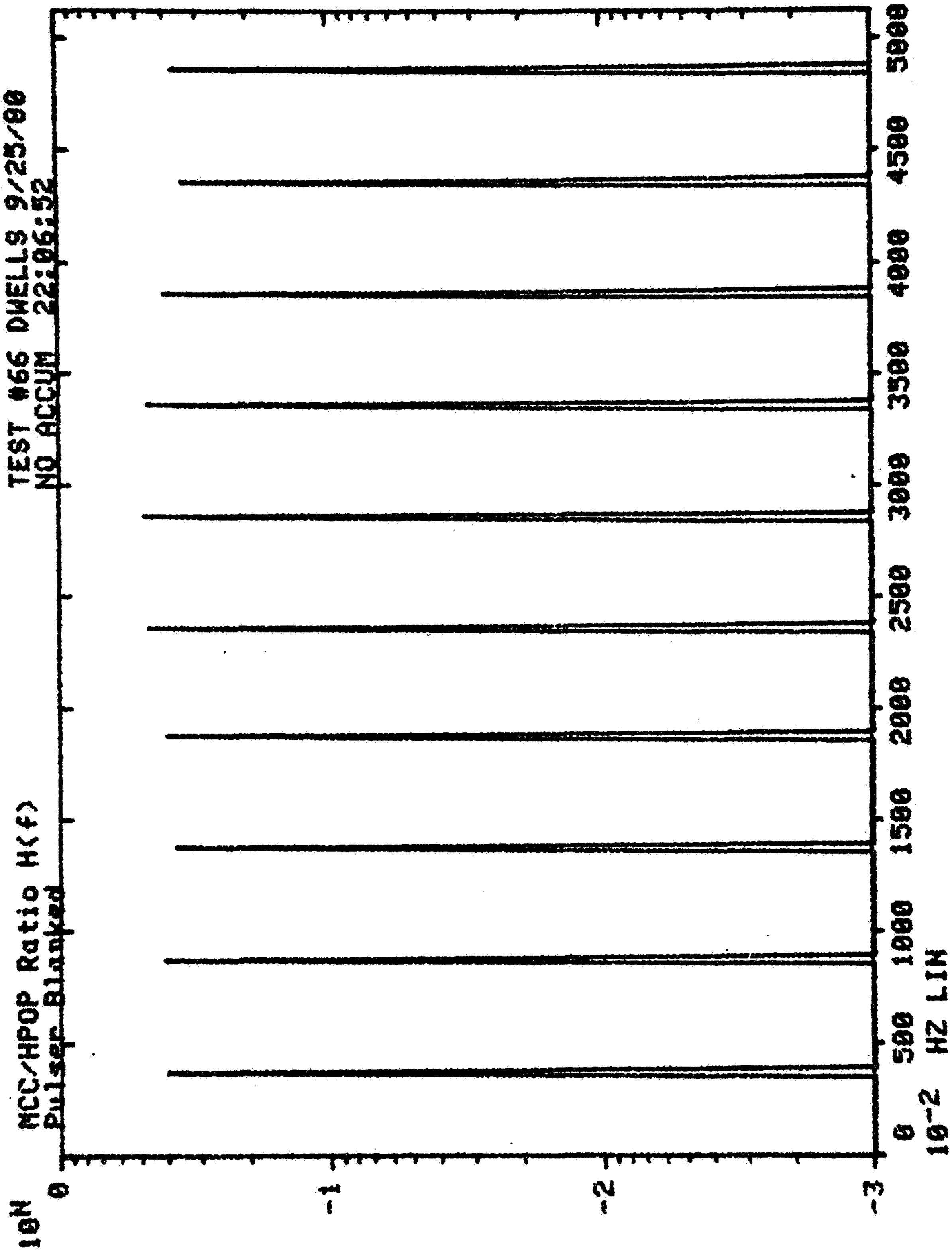

DEG HPOP/LPOP Ratio H(f) - Polar TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E8

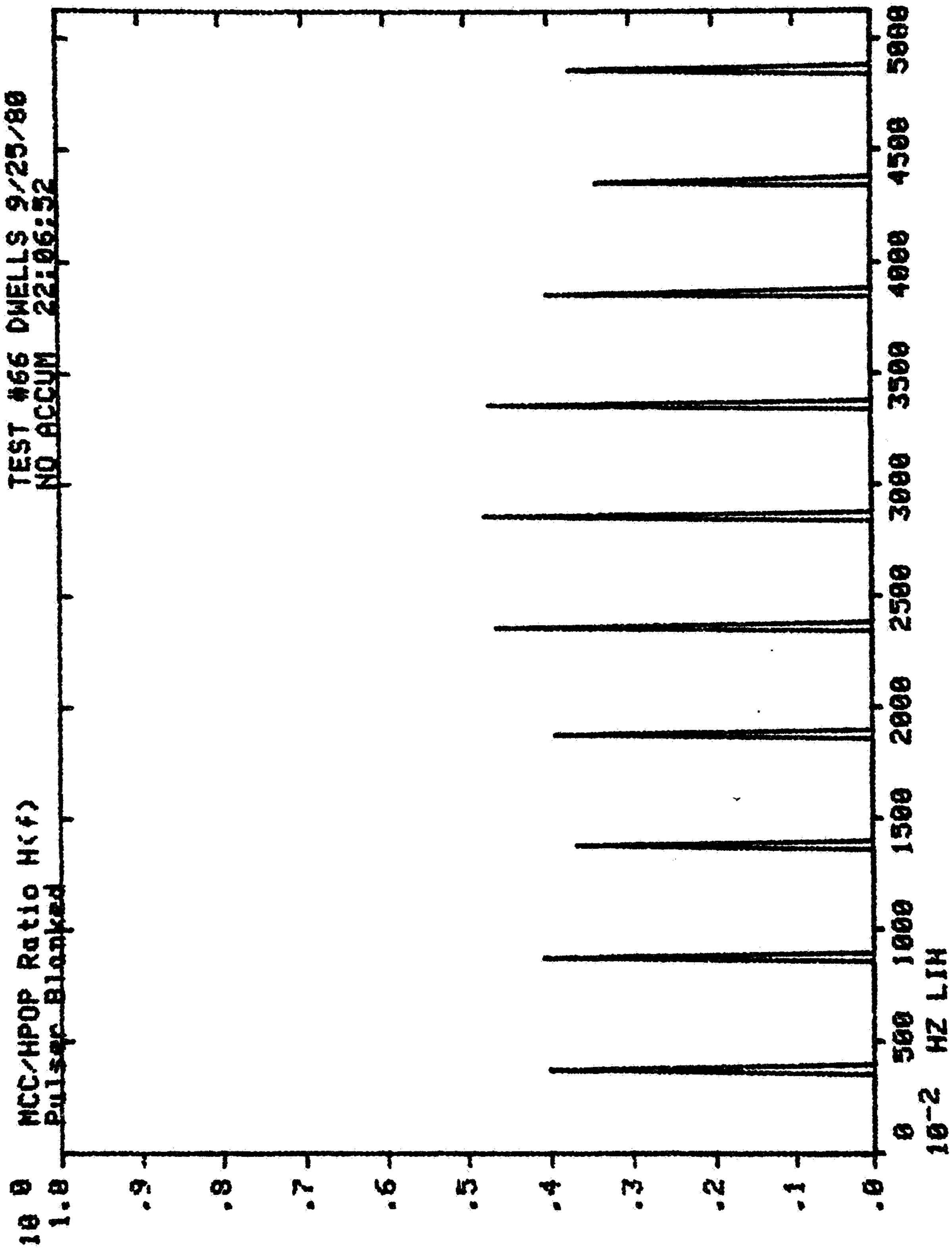


HPOP/LPOP Ratio Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

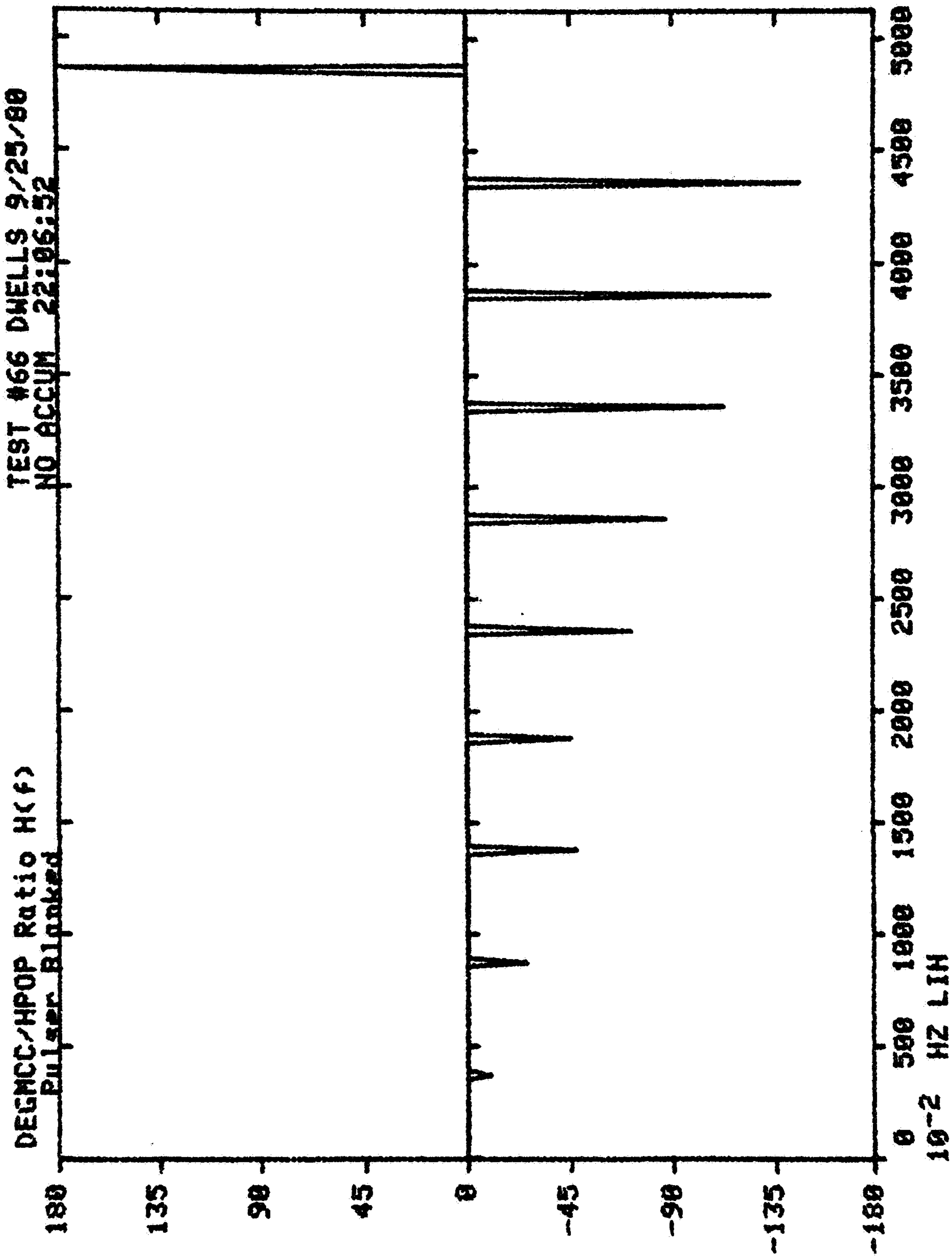
E9


MCC/HPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/90
NO ACCUM 22:06:52
10N
0
-1
-2
-3
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

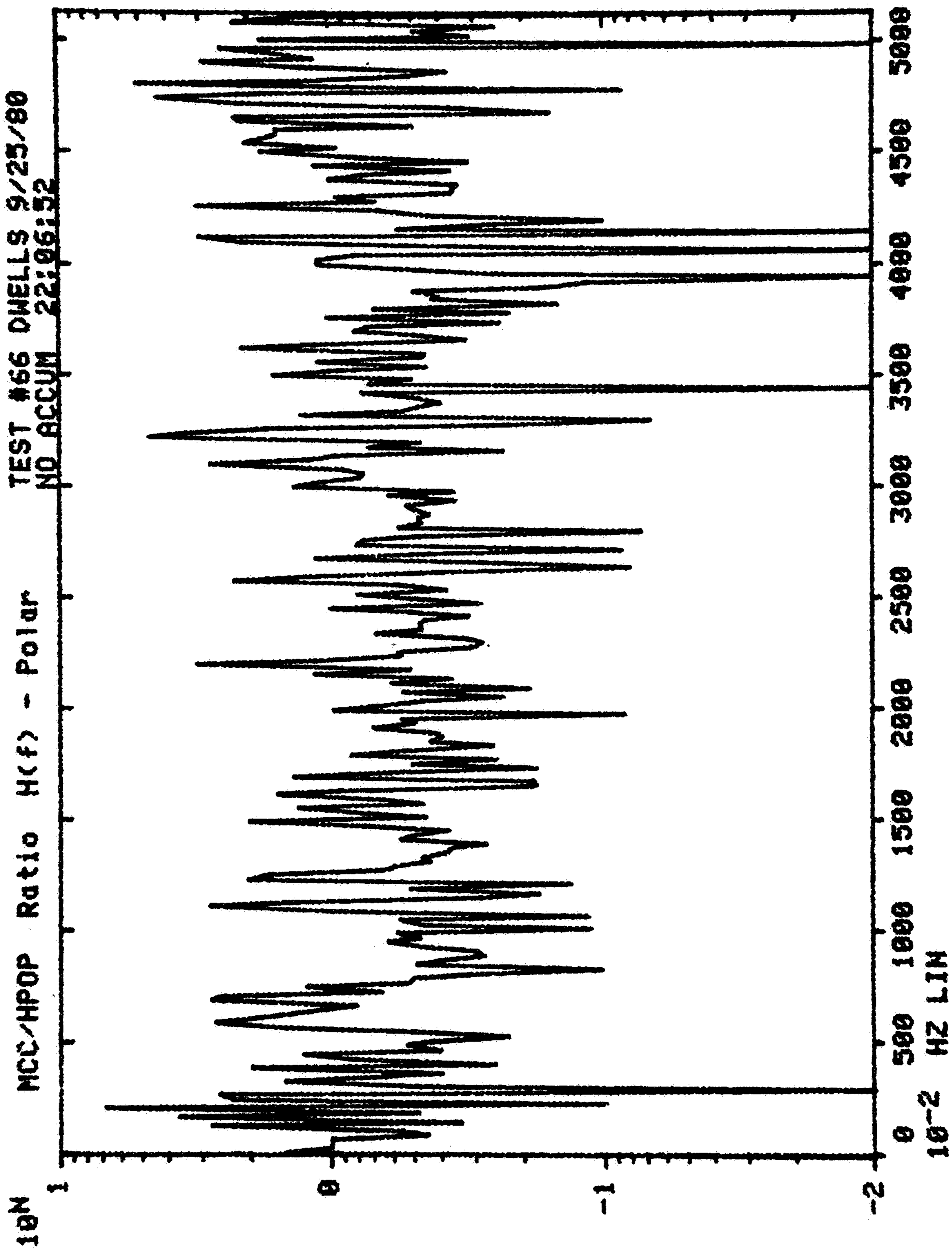
E10



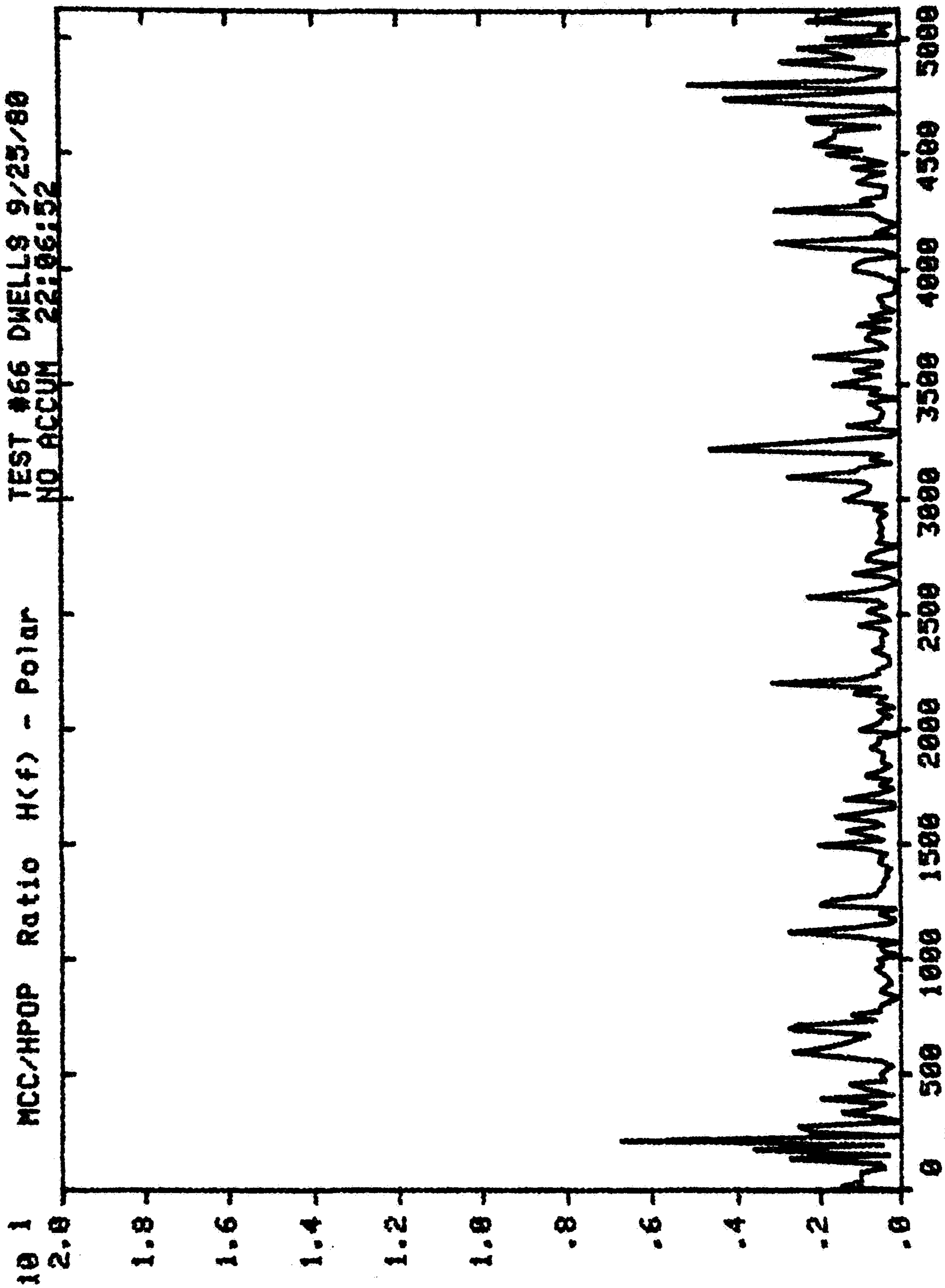
MCC/HPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN


DEGMCC/HPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^{-2} HZ LIN

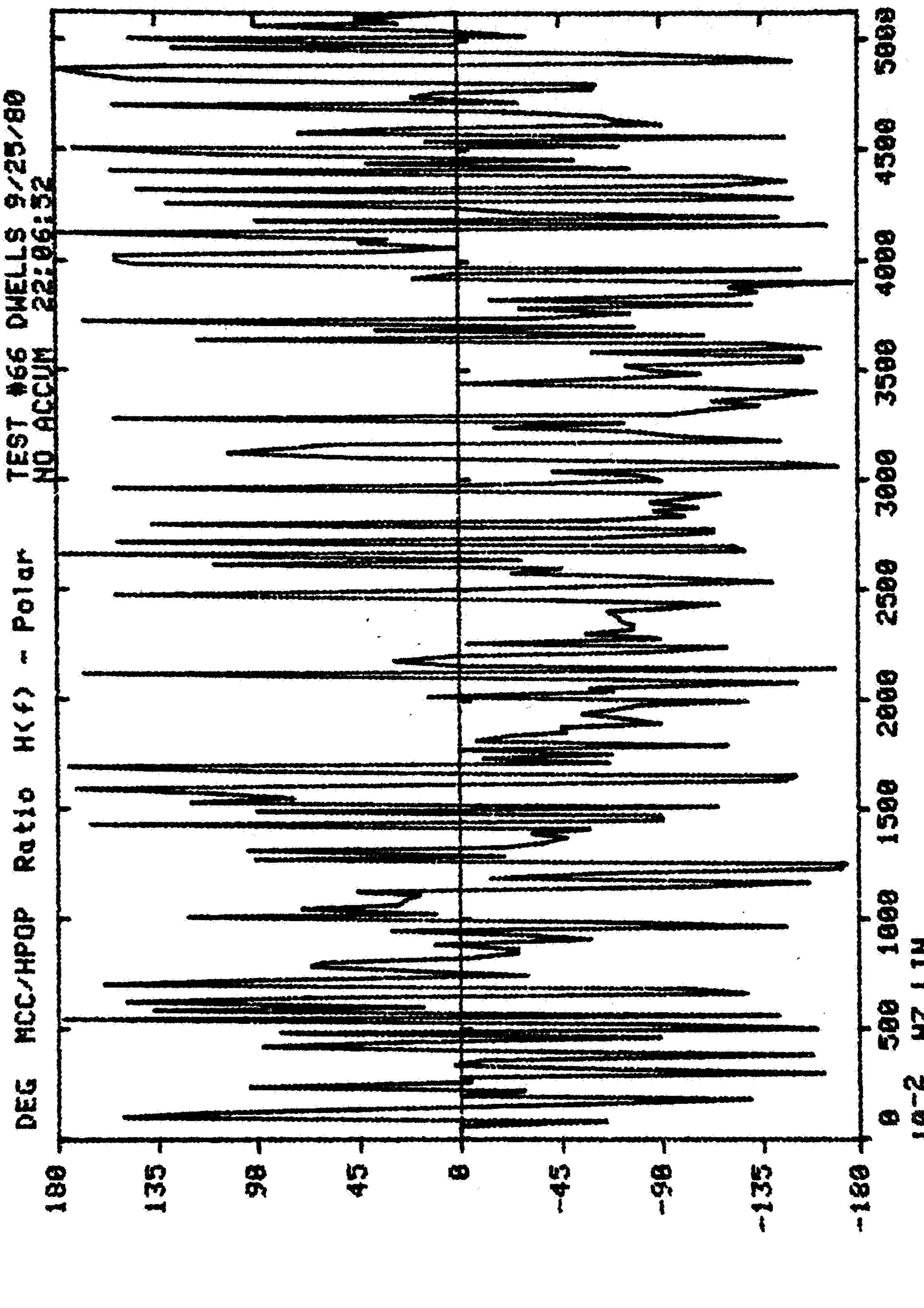
E12


MCC/HPOP Ratio H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

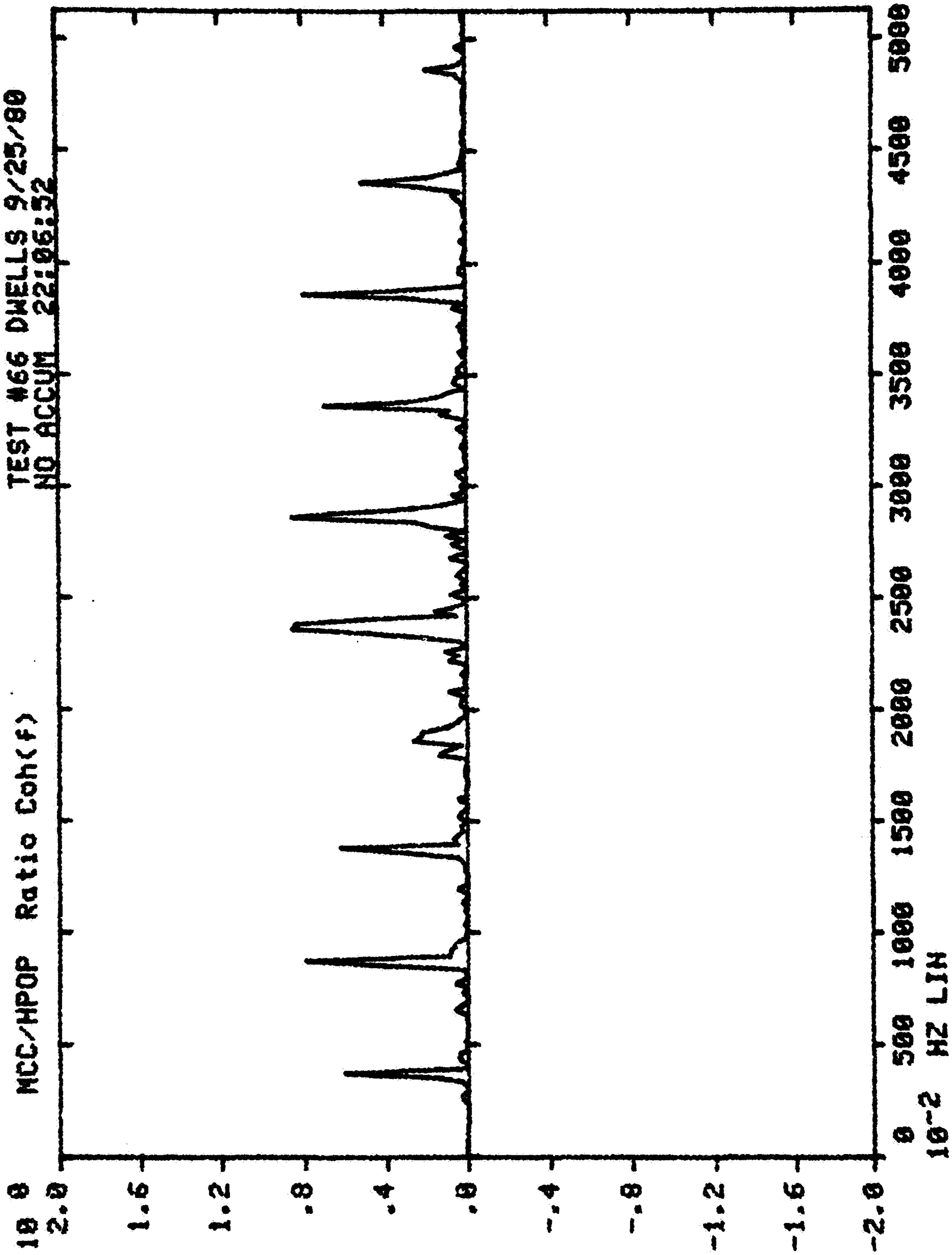
E13


MCC/HPOP Ratio H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

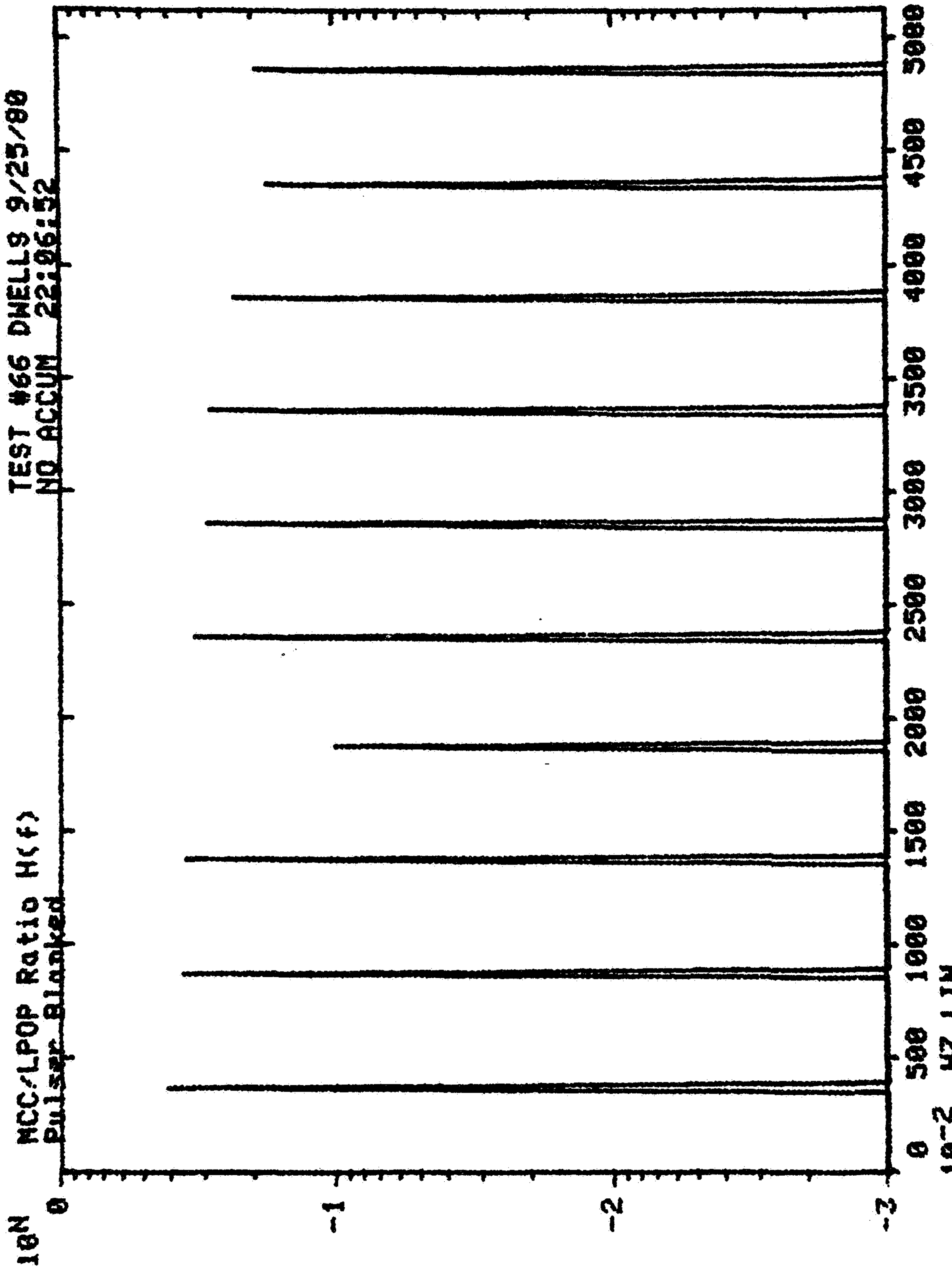
E14


DEG MCC/HPOP Ratio H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

E15

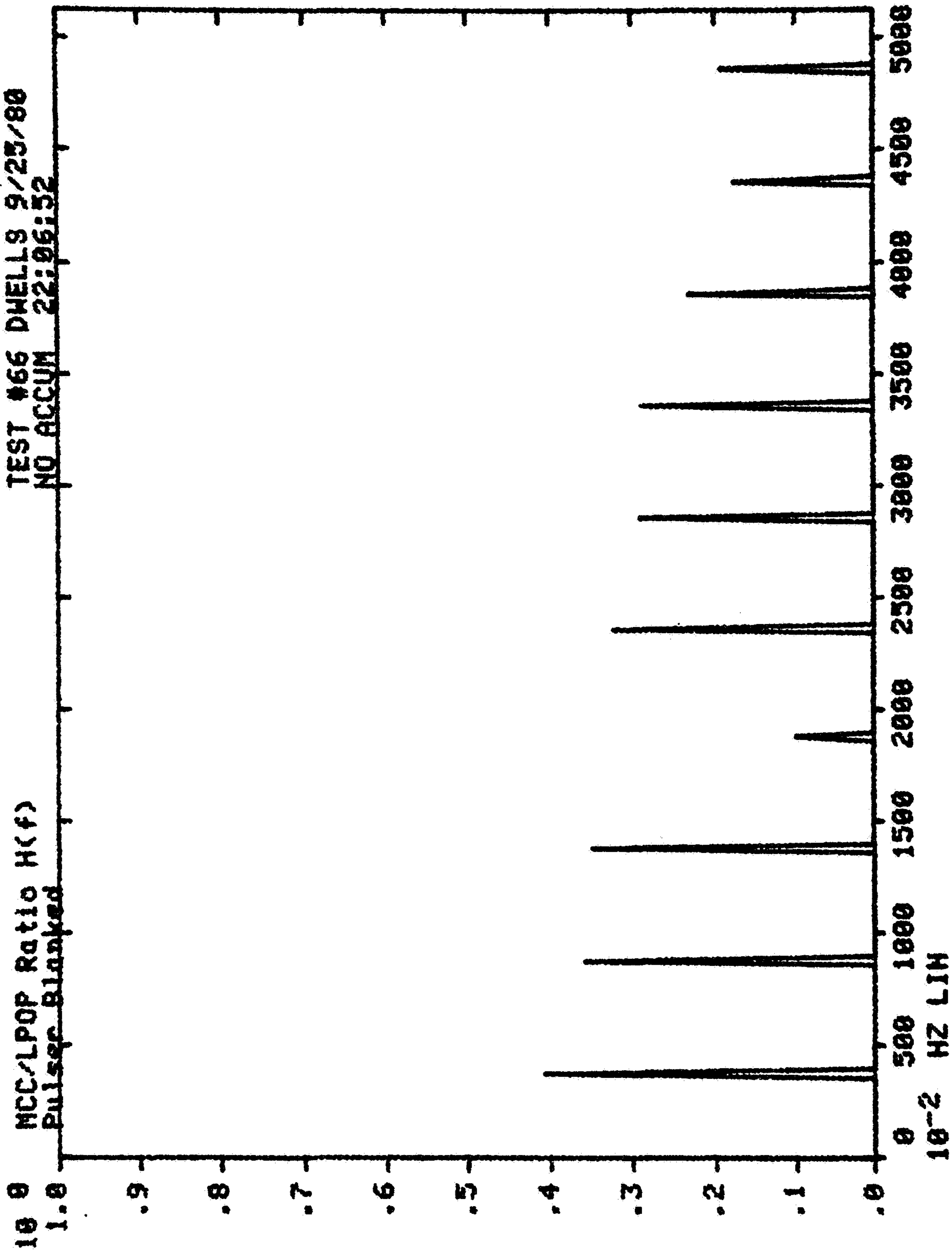

MCC/HPOP Ratio Coh(F)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E16

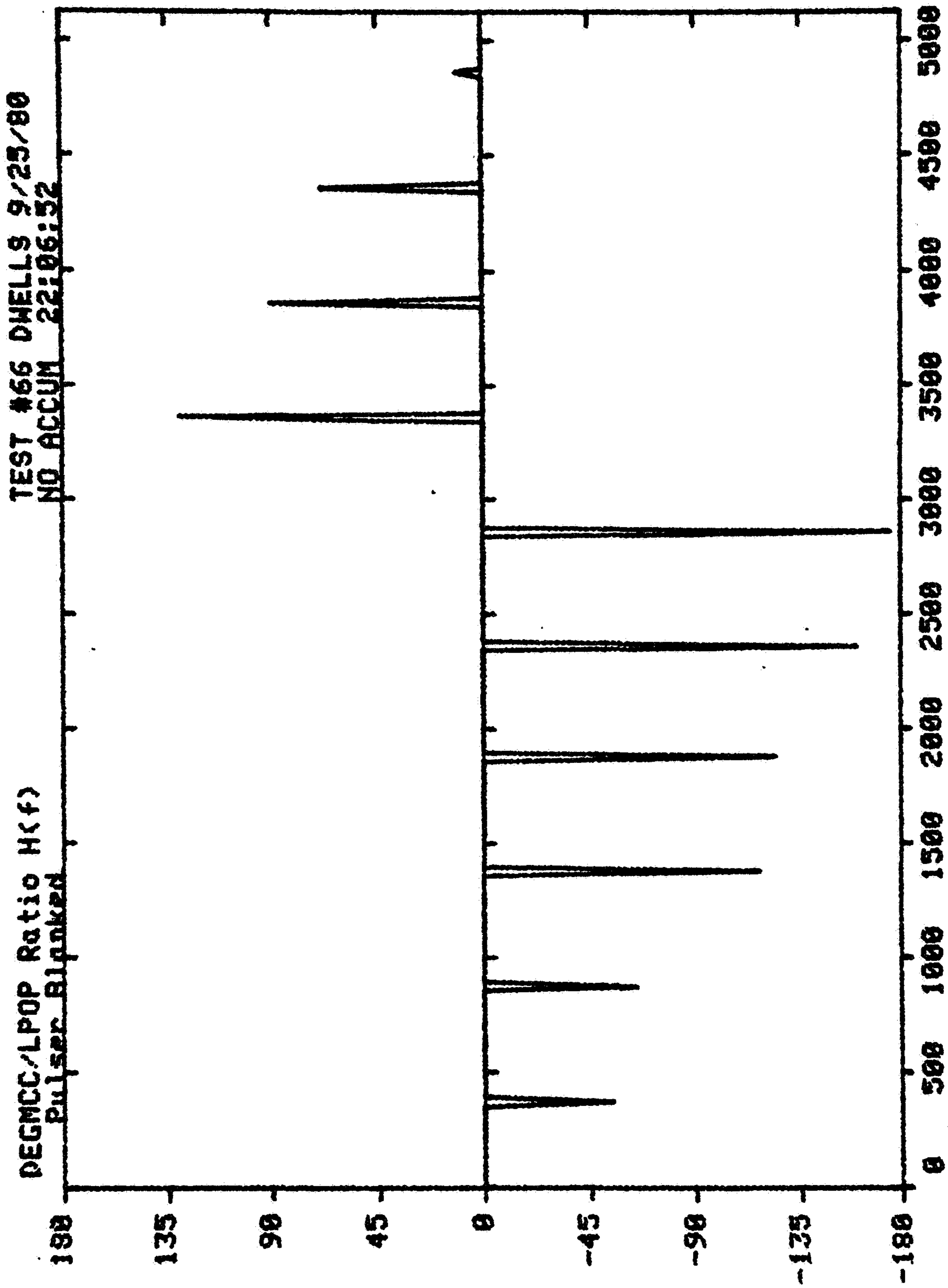


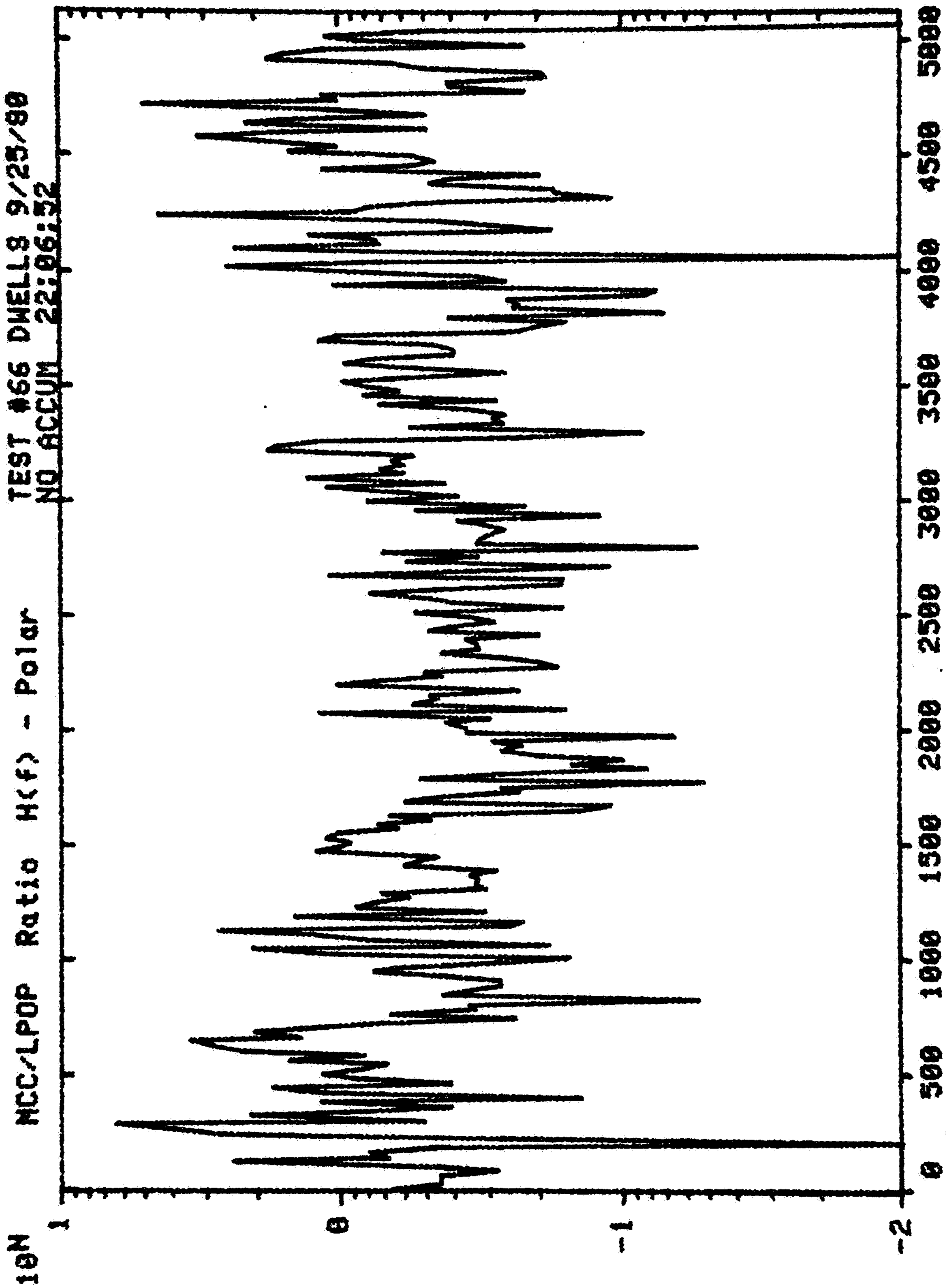
MCC/LPOP Ratio H(f)
Pulsar Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
0
-1
-2
-3
10-2 HZ LIN
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

E17

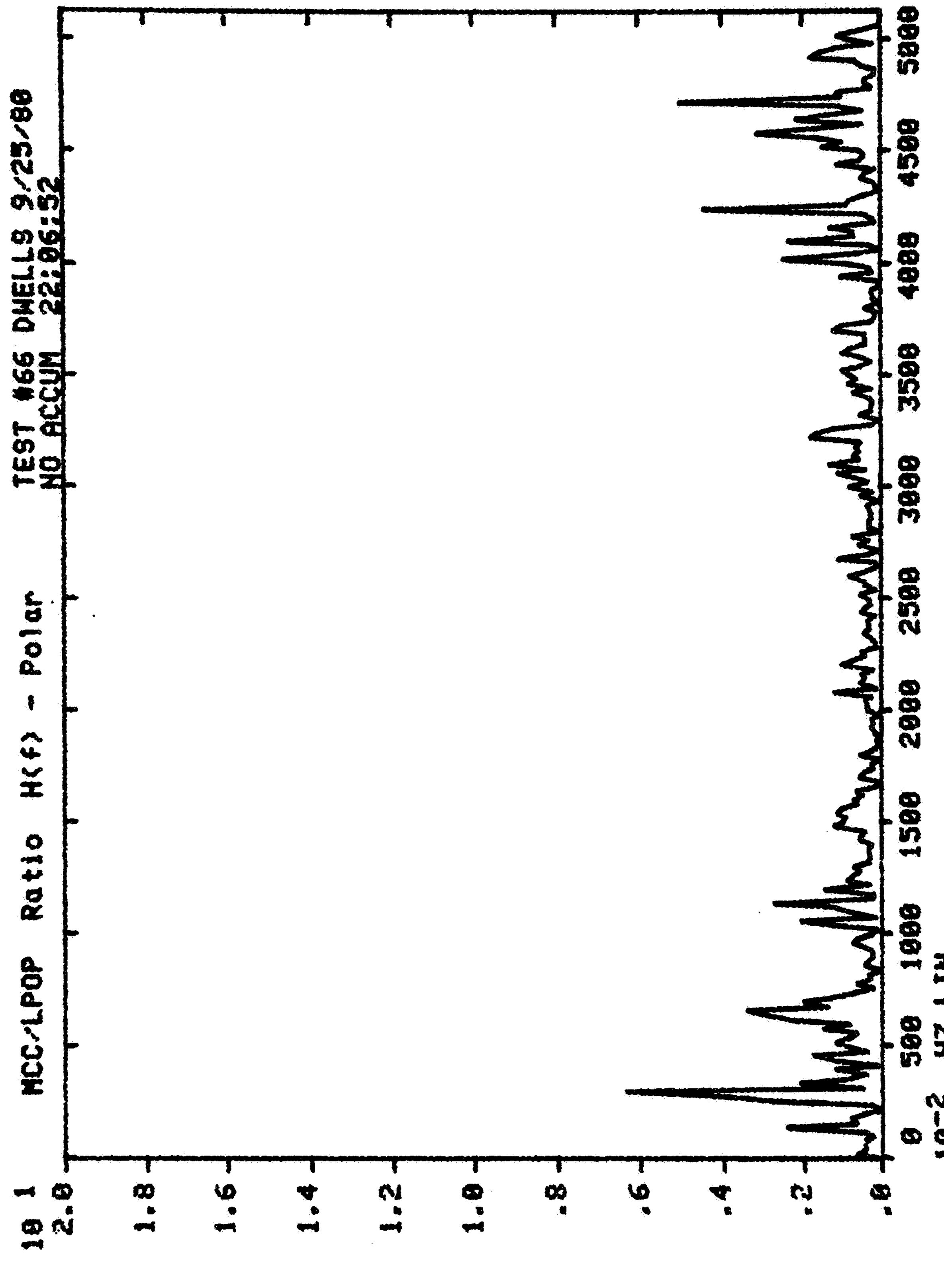

MCC/LPOP Ratio H(f)
Pulses Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E18

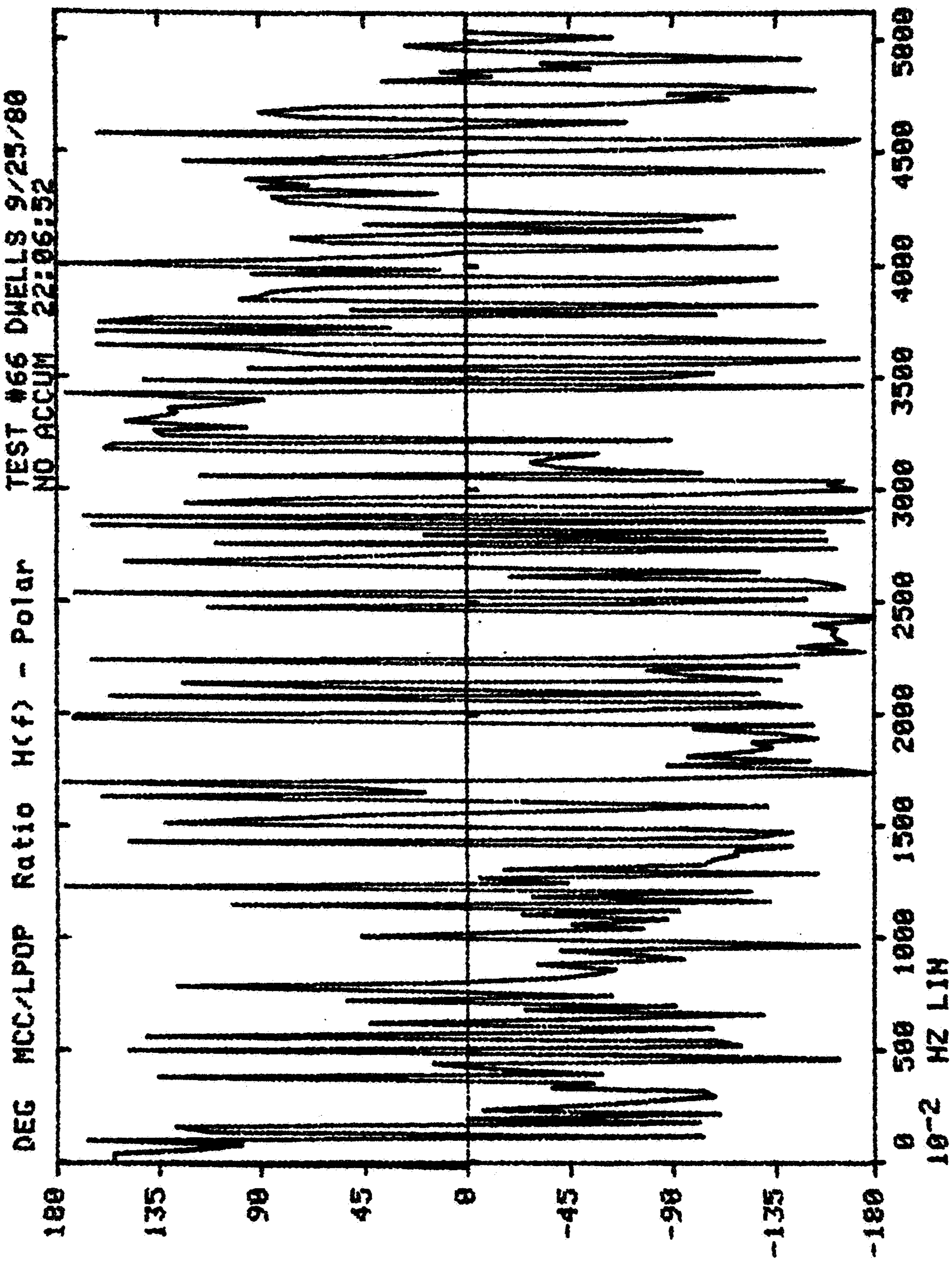

DEGMCC/LPOP Ratio H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


NCC/LPOP Ratio H(f) - Polar
TEST #66 DWELL9 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E20

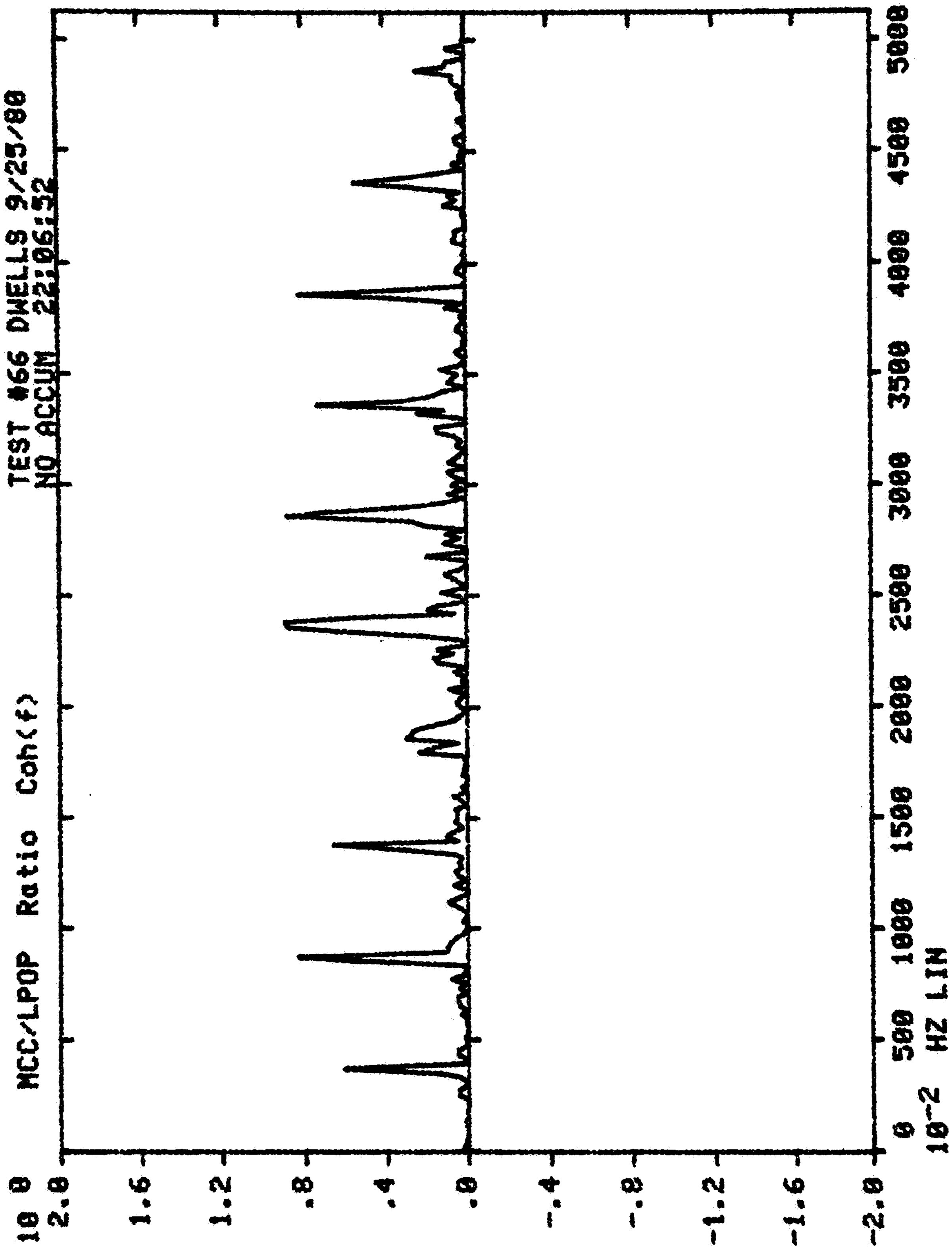


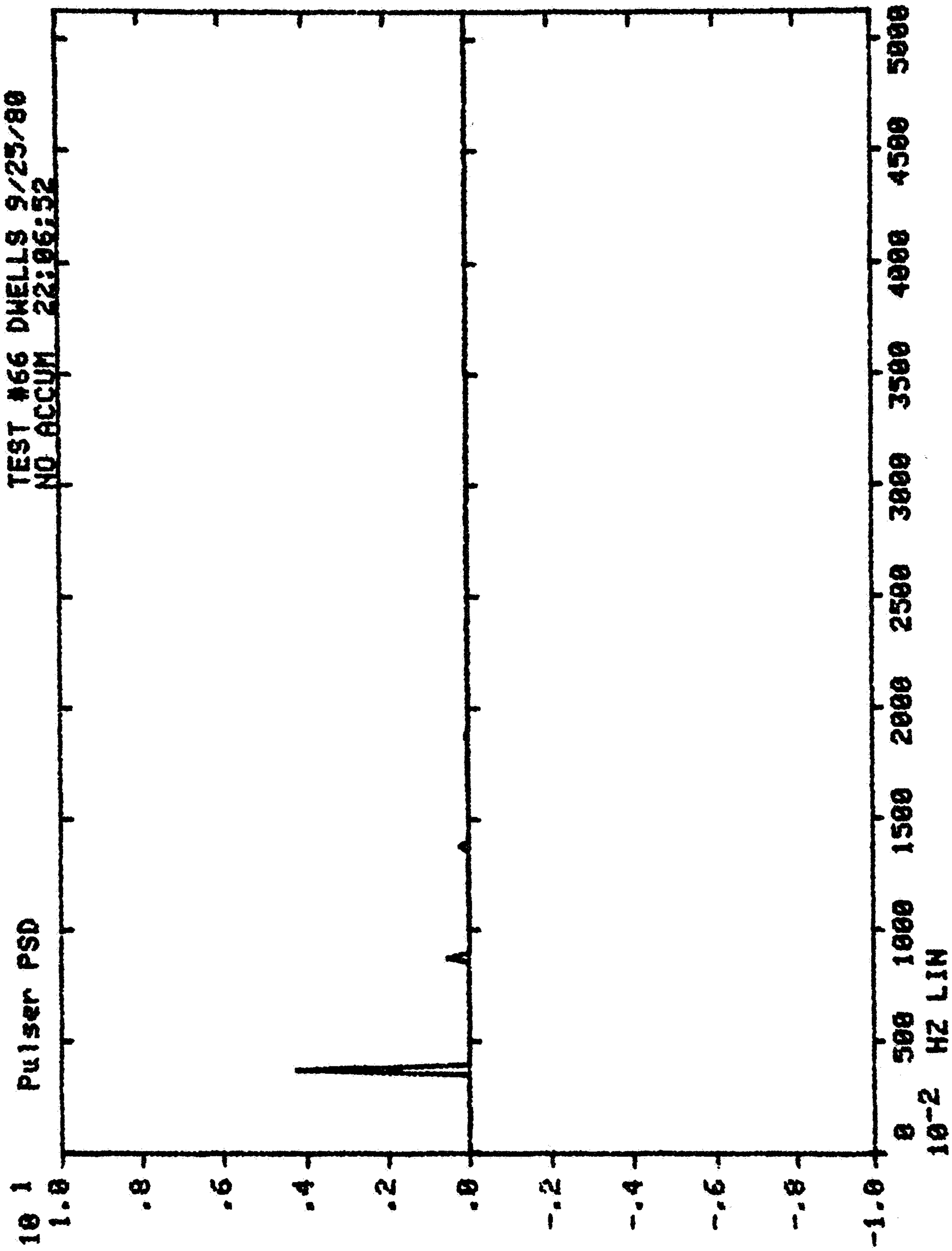
MCC/LPOP Ratio H(f) - Polar
TEST #66 DWELL9 9/25/80
NO ACCUM 22:06:52
10 1
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN



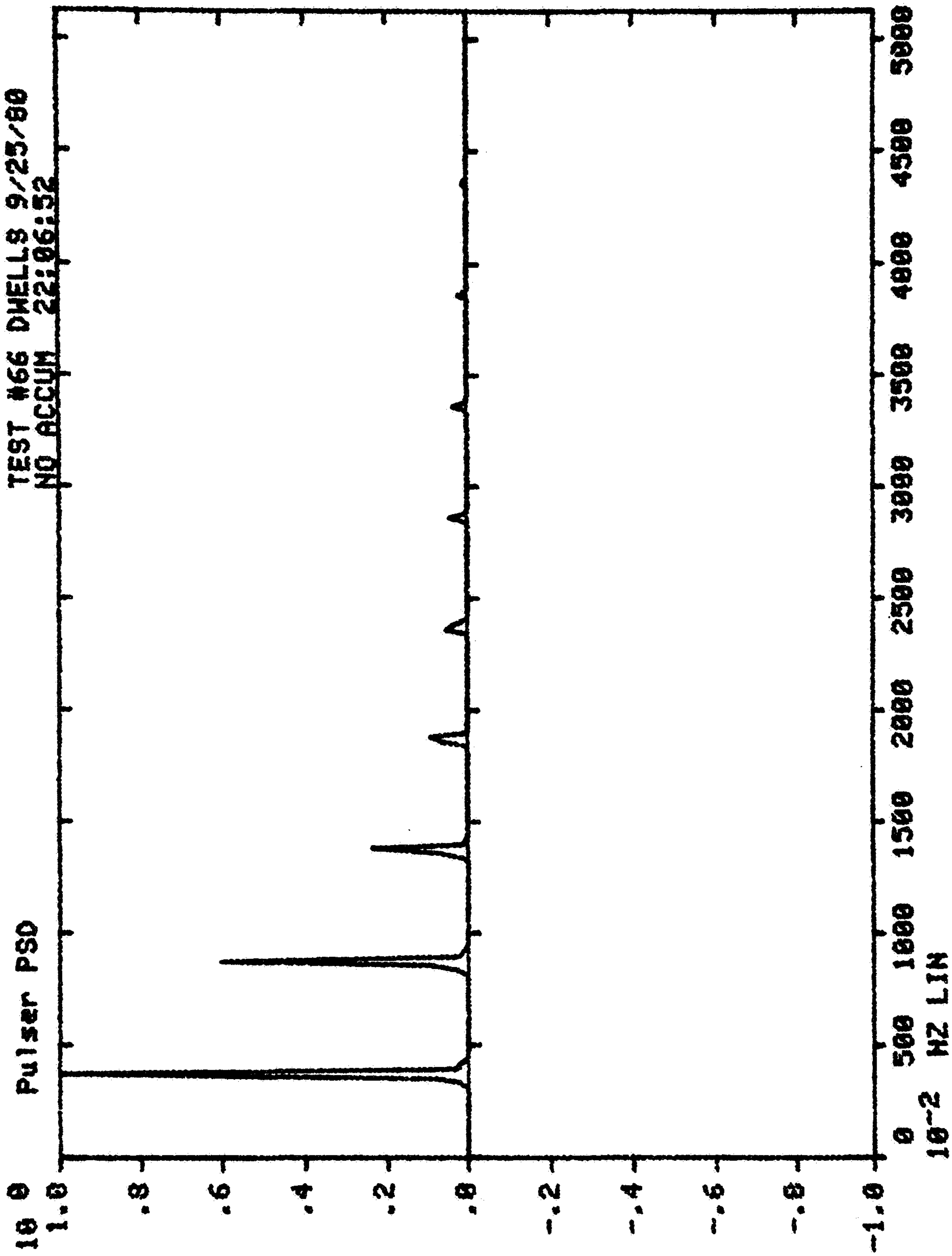
DEG MCC/LPOP Ratio H(f) - Polar TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E22

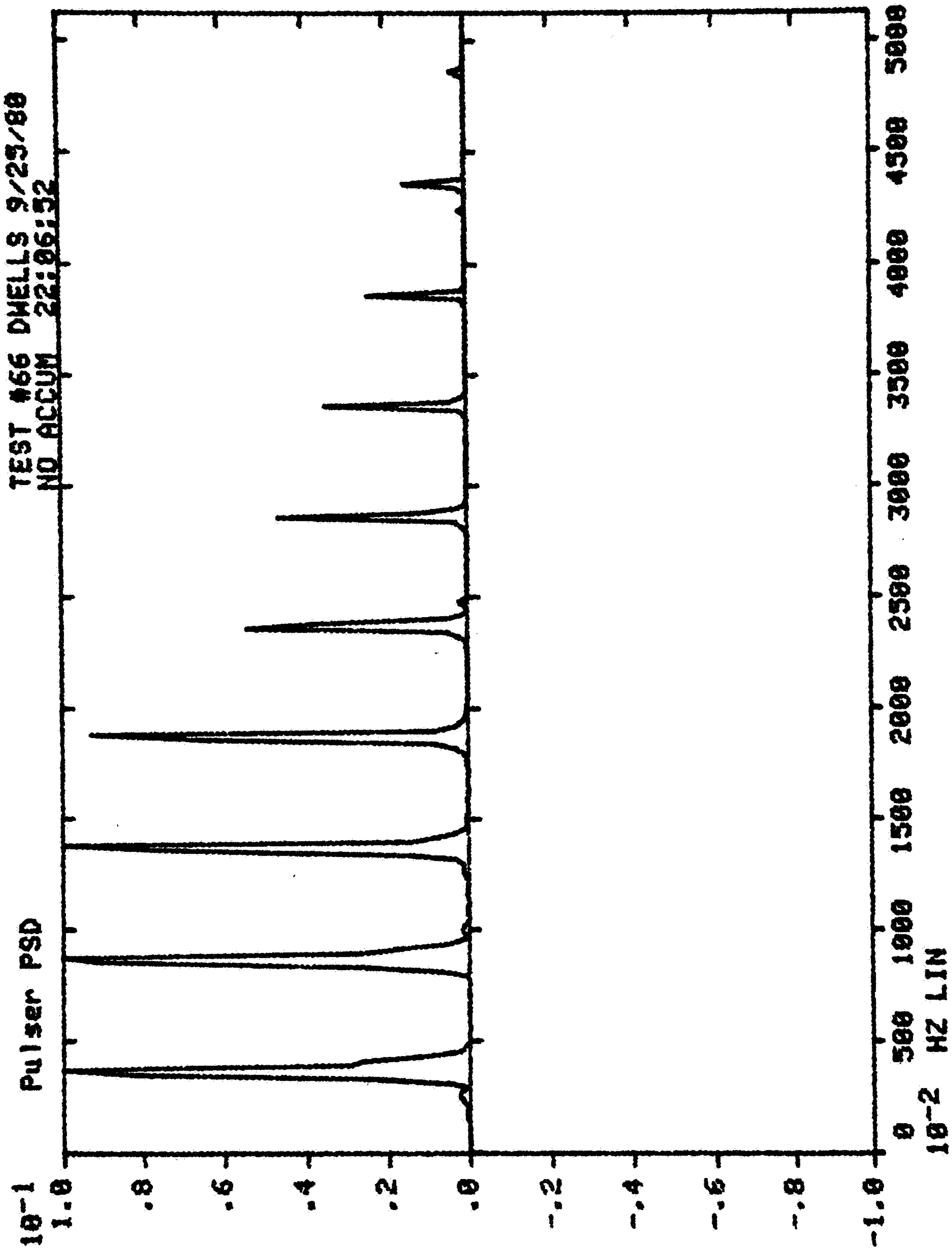

MCC/LPOP Ratio Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
Pulser PSD
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

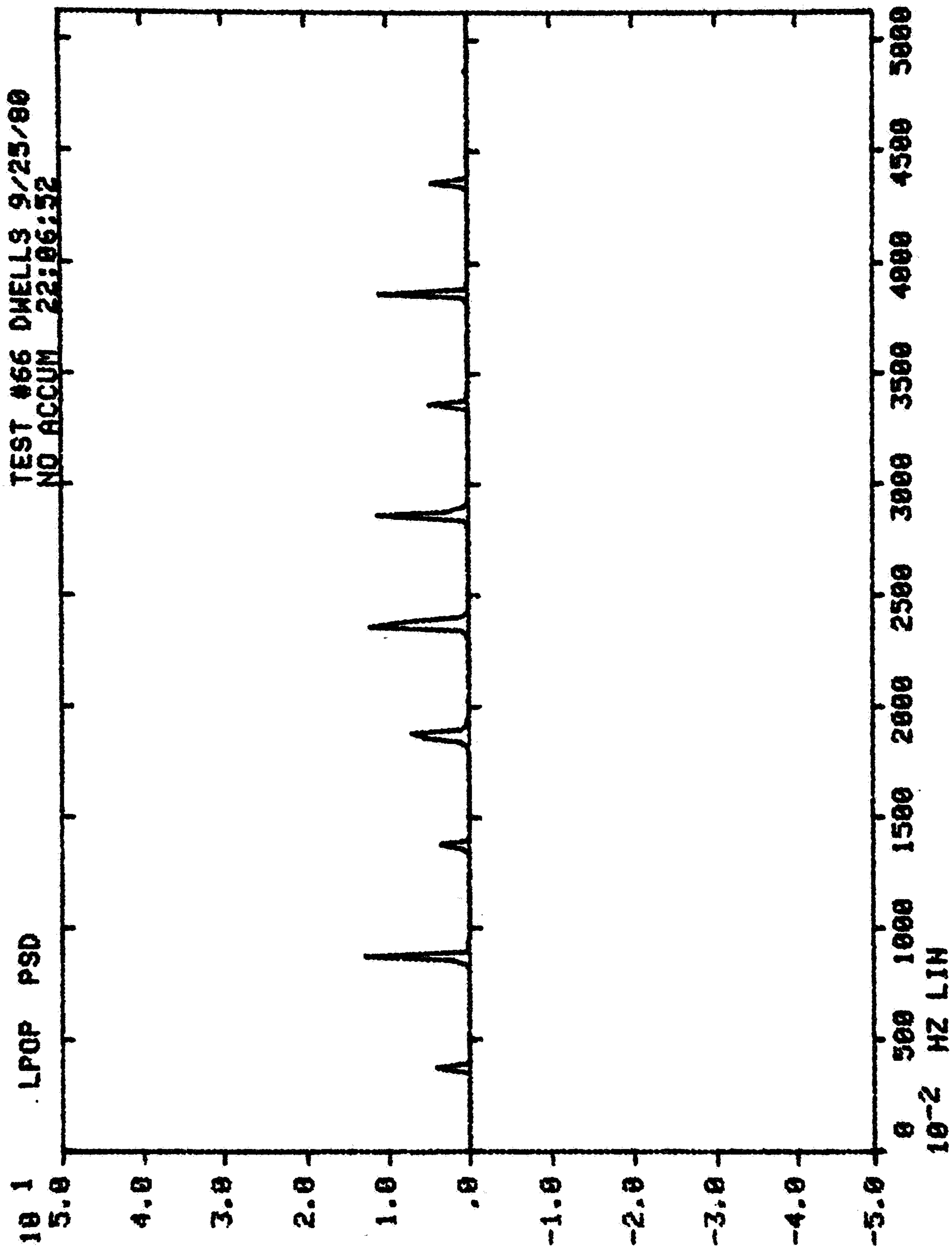
E24



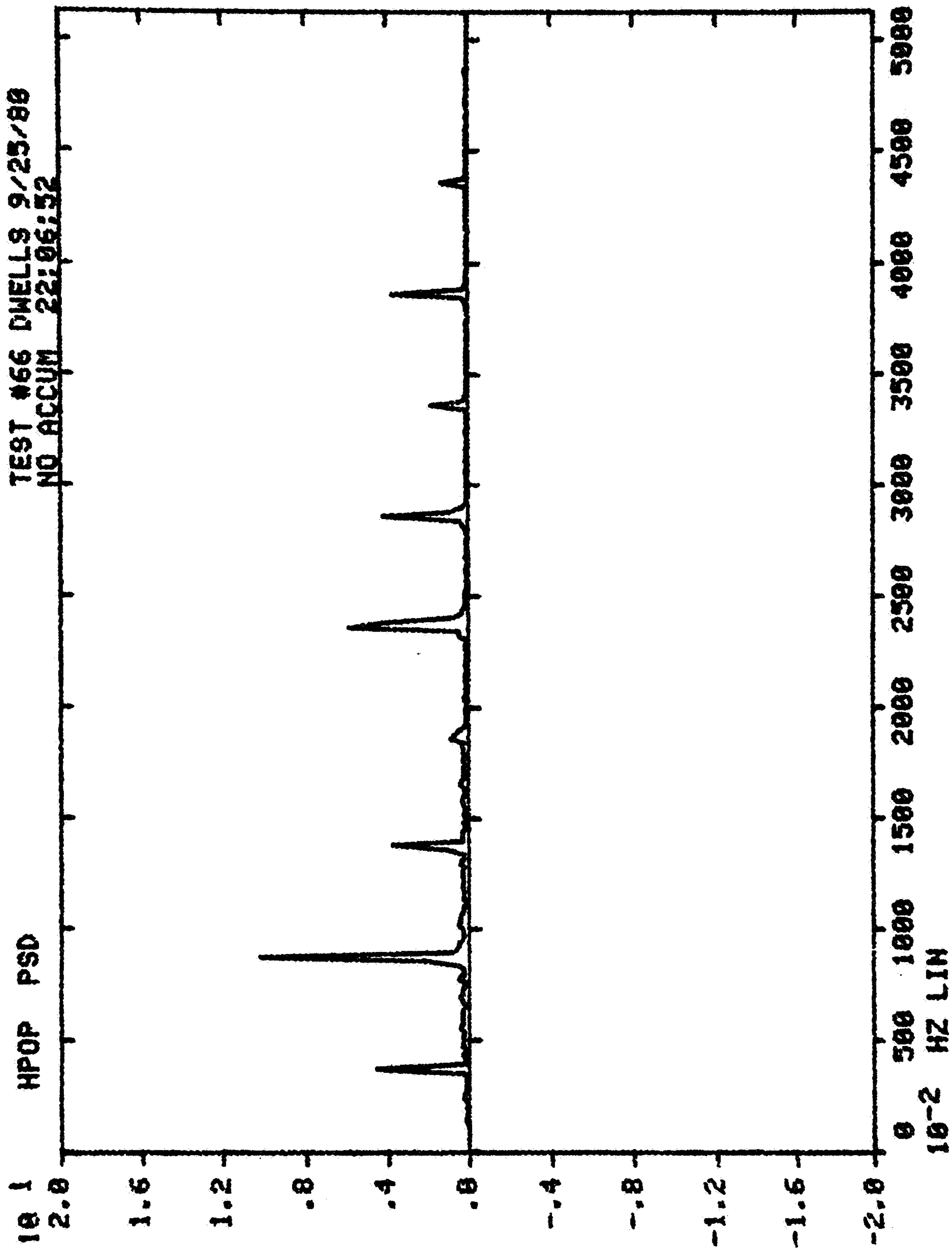
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
Pulser PSD
10 0
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


Pulser PSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
10^-1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

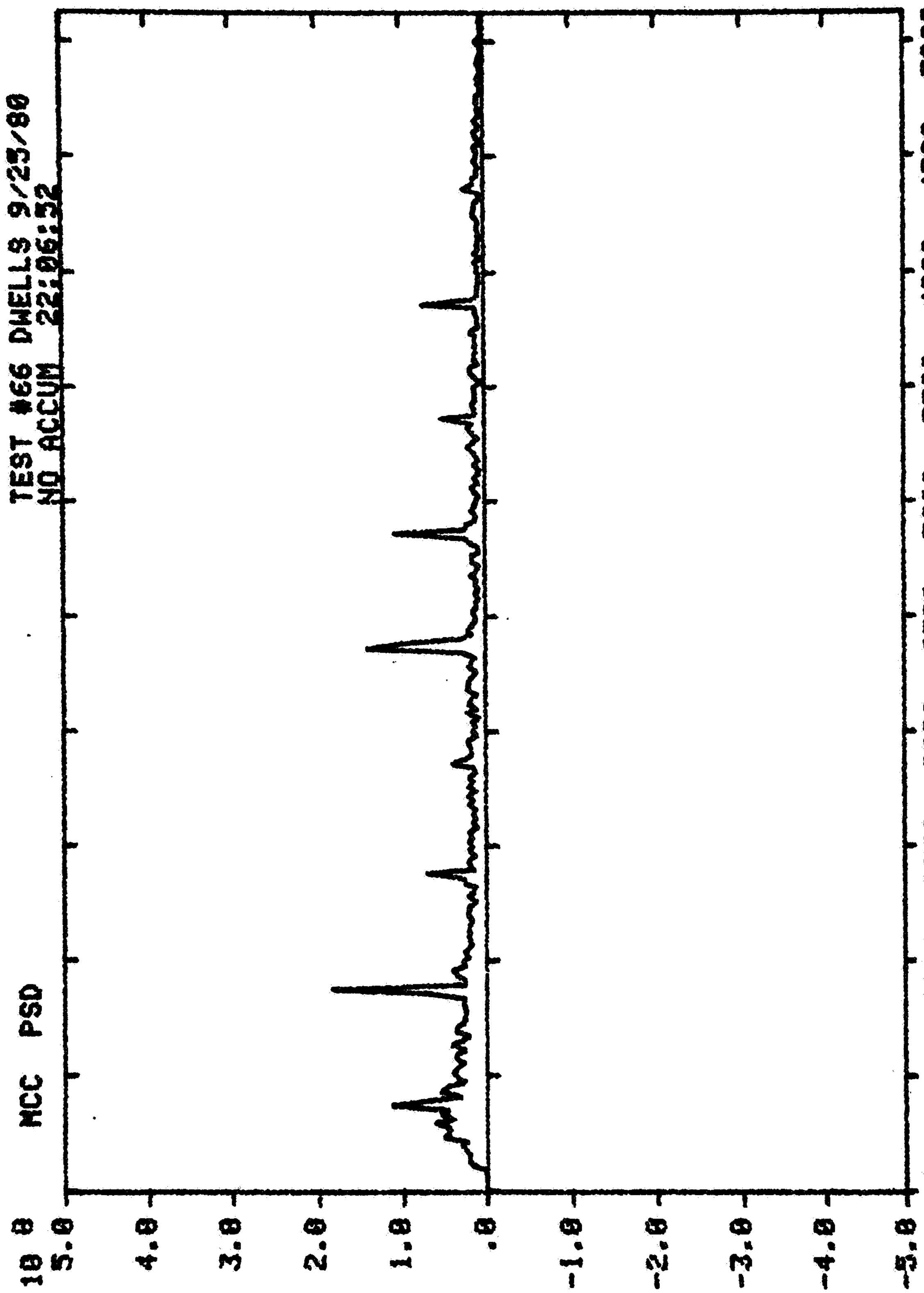
E26


LPOP PSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
5.0
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
-5.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

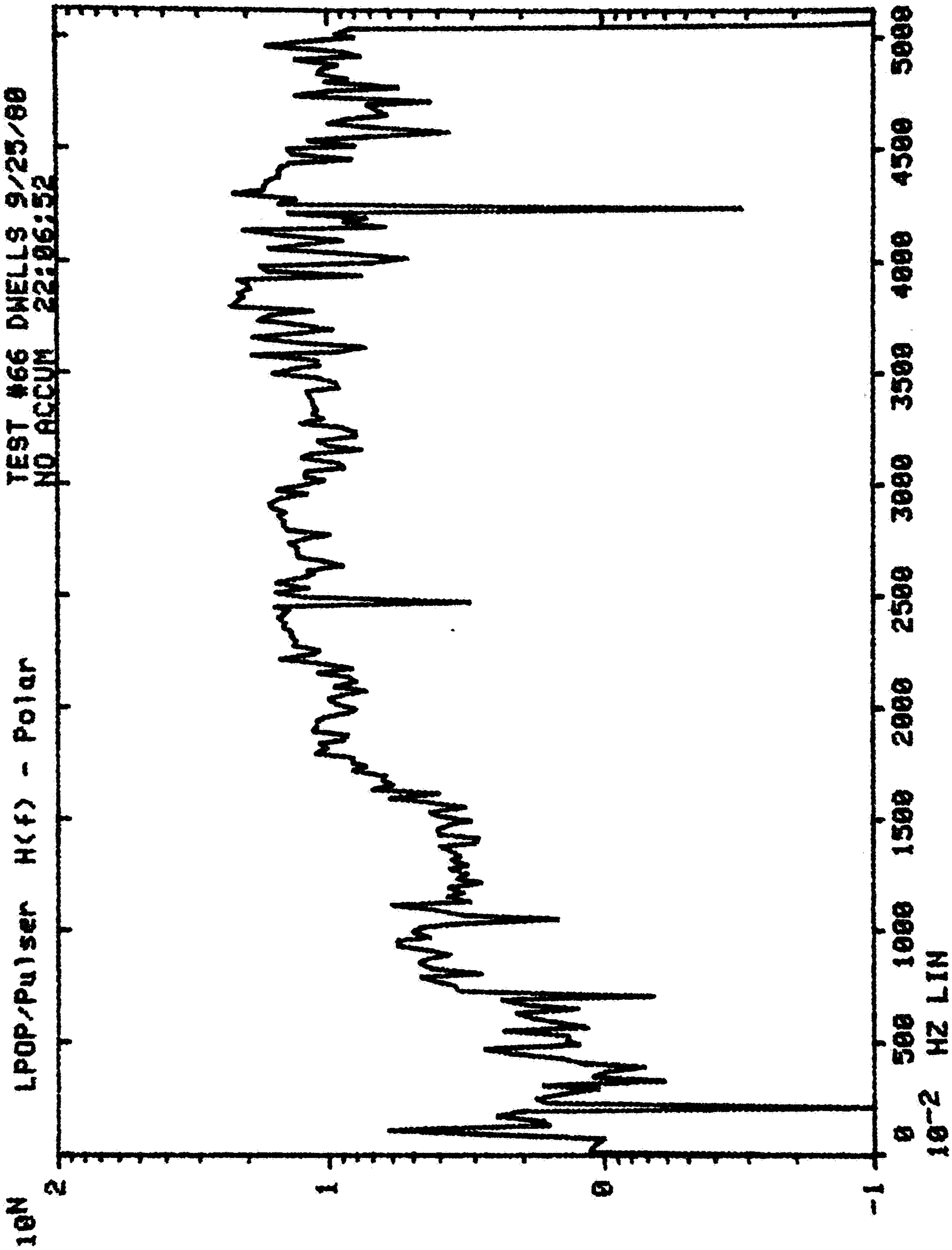
E27


HPOP PSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

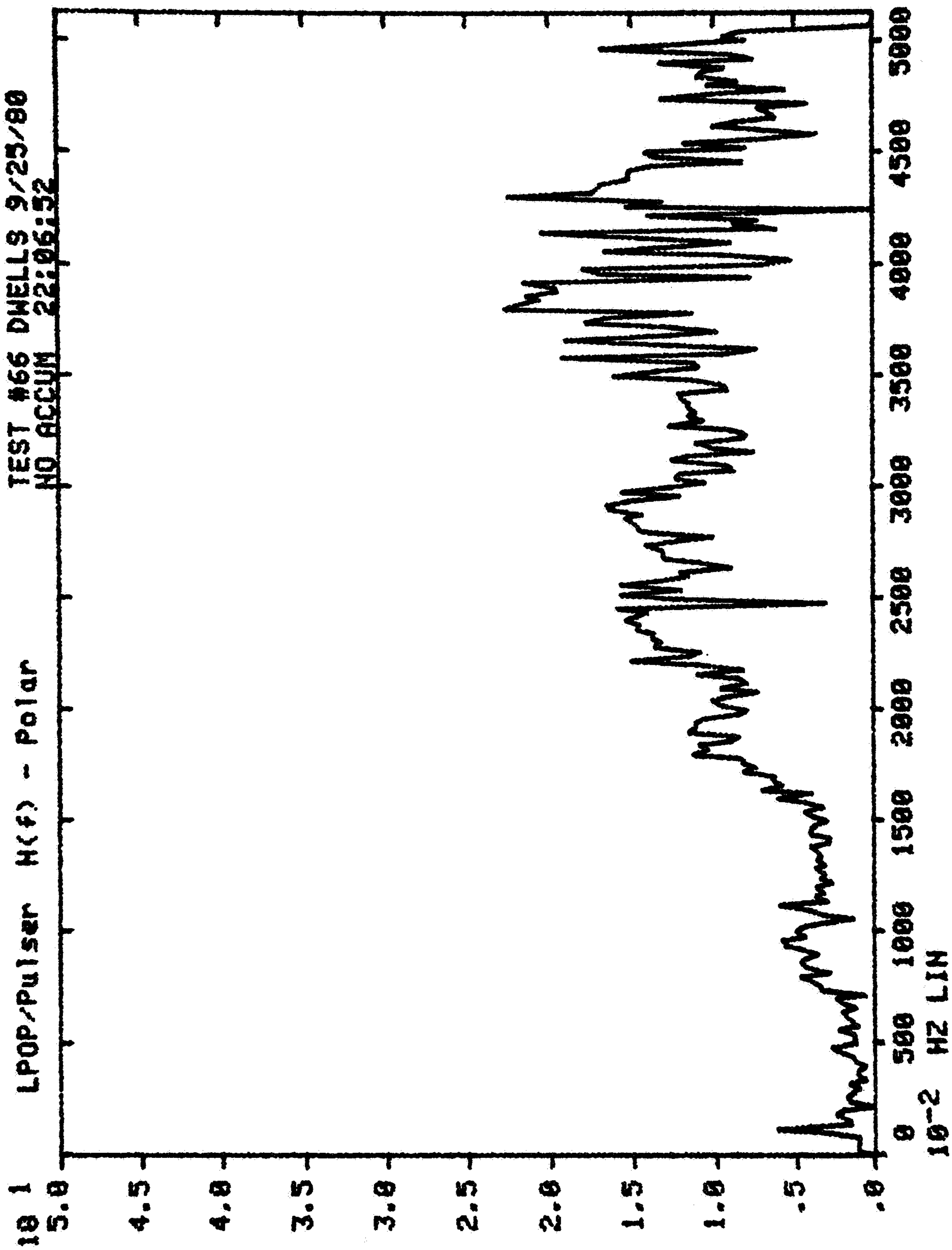
E28



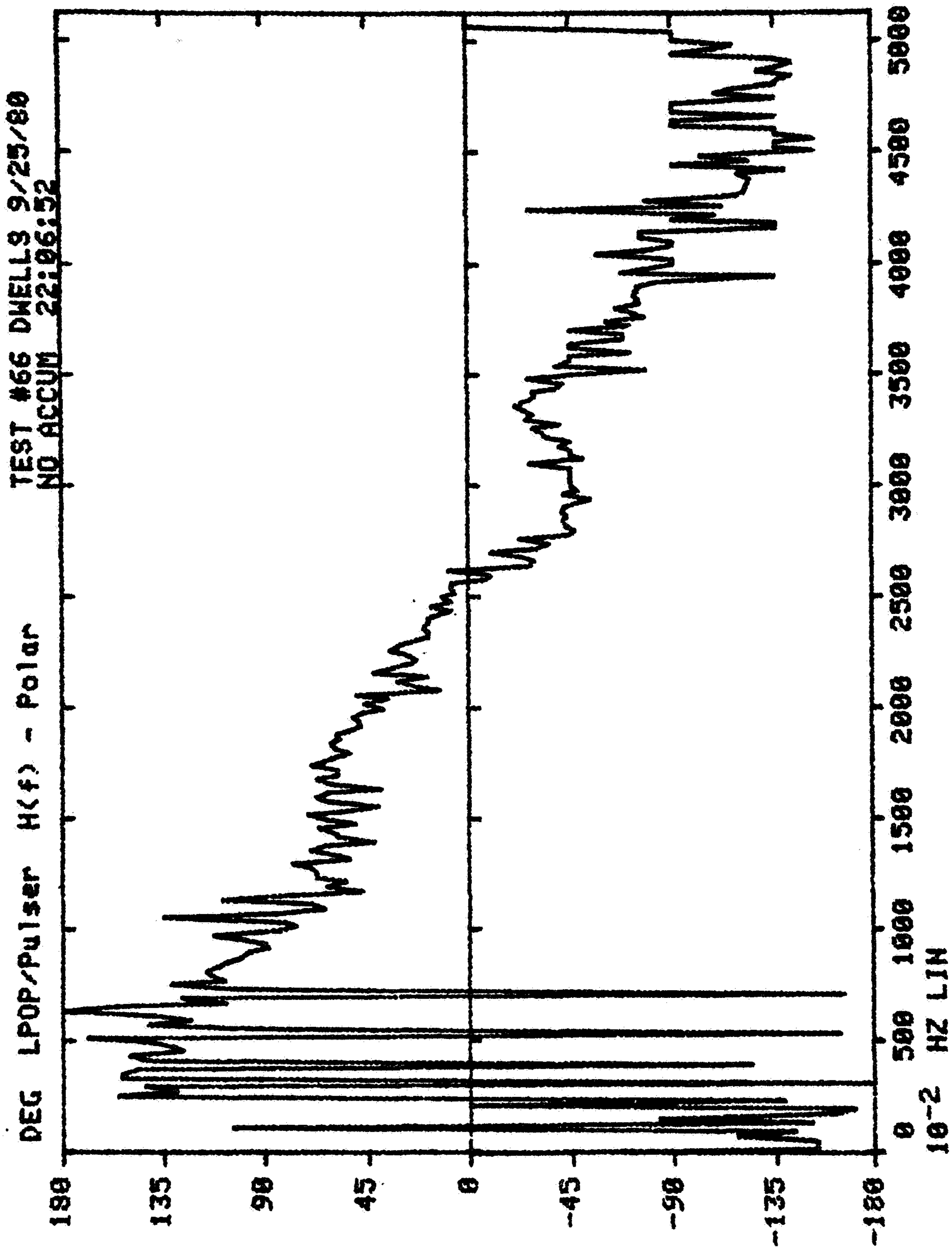
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
MCC PSD
10^-2 HZ LIN
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10 0
5.0
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
-5.0


LPOP/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E30

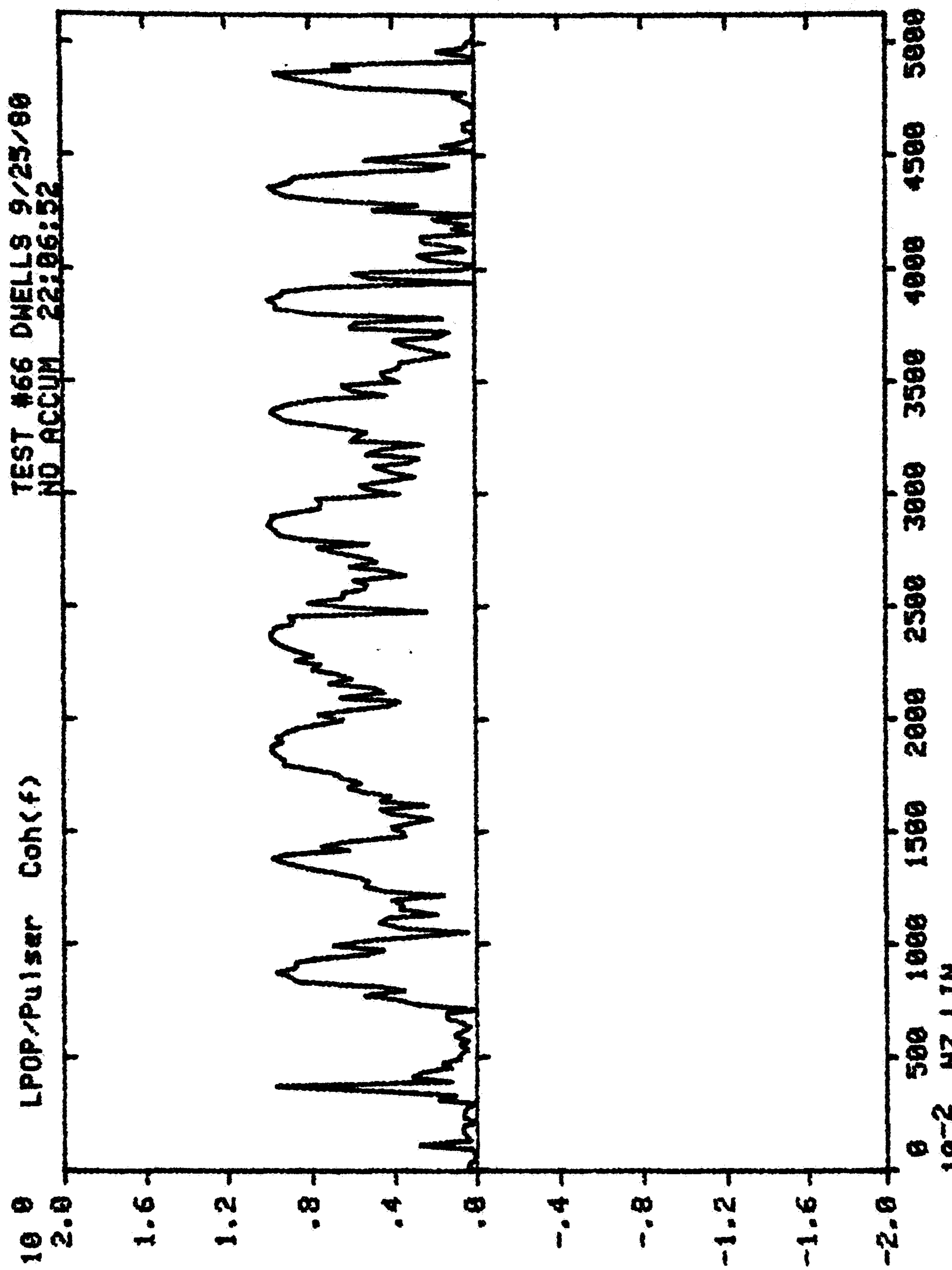


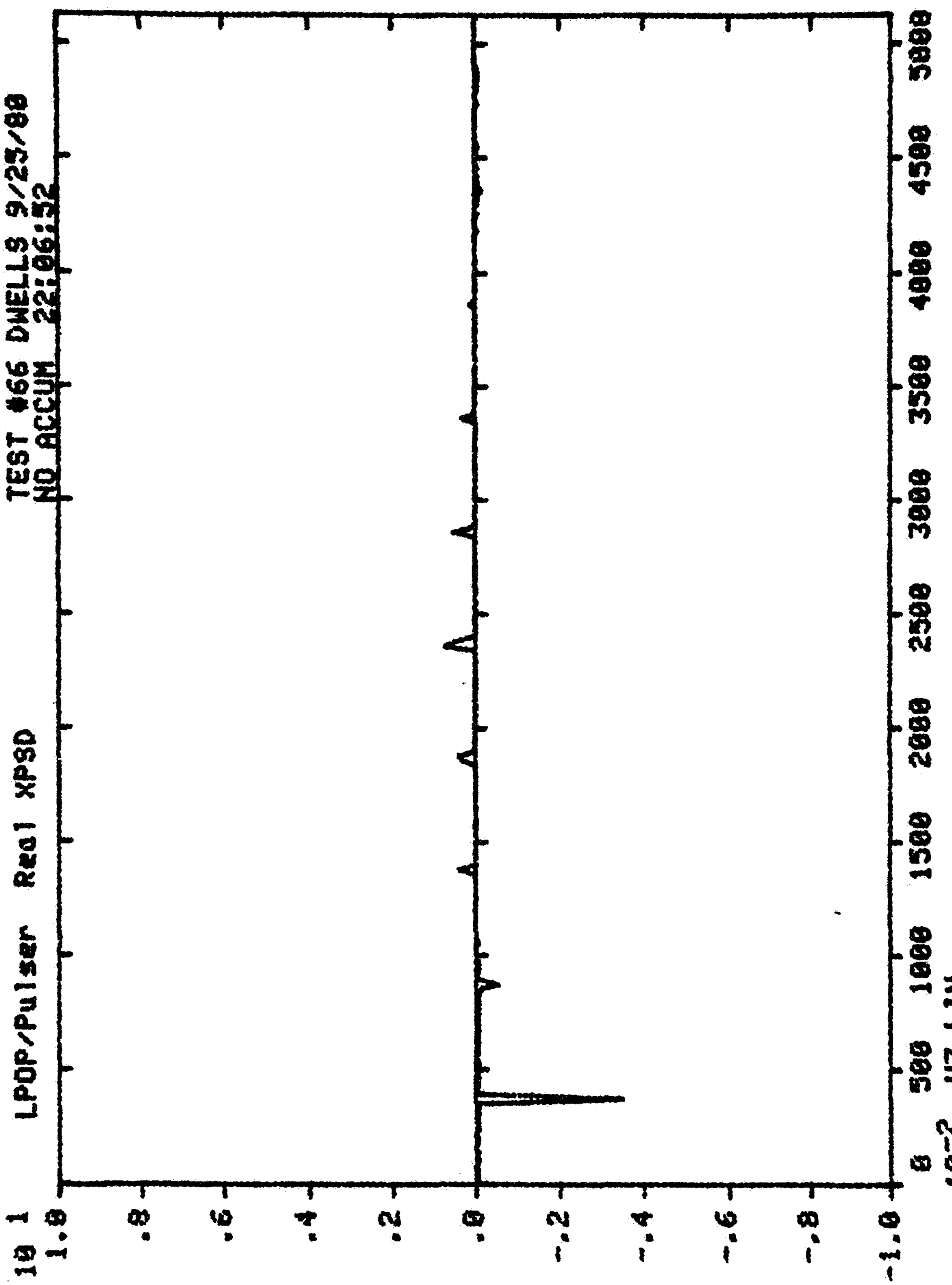
LPOP/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN



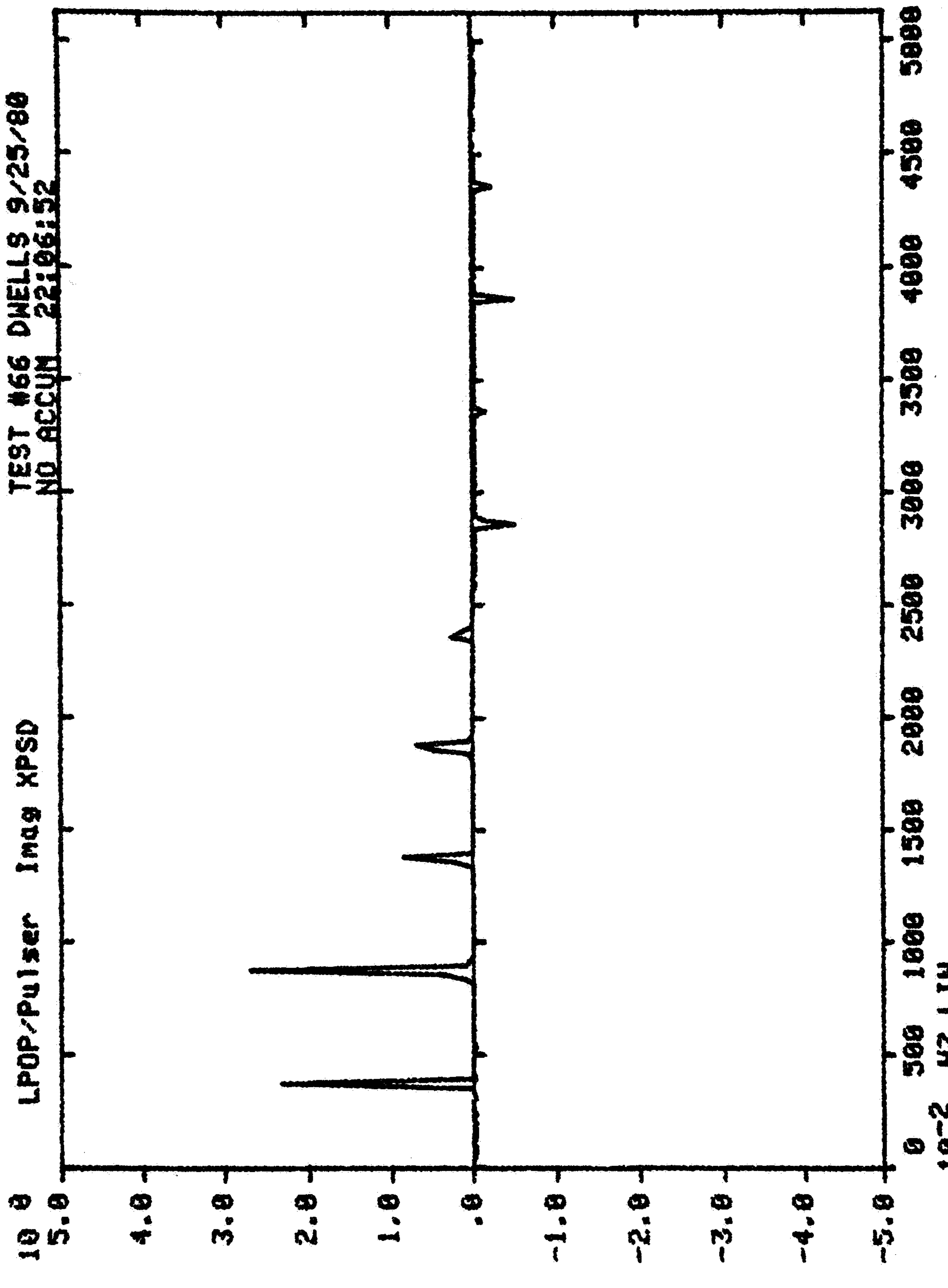
DEG LPOP/Pulser H(f) - Polar
TEST #66 DWELL9 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E32

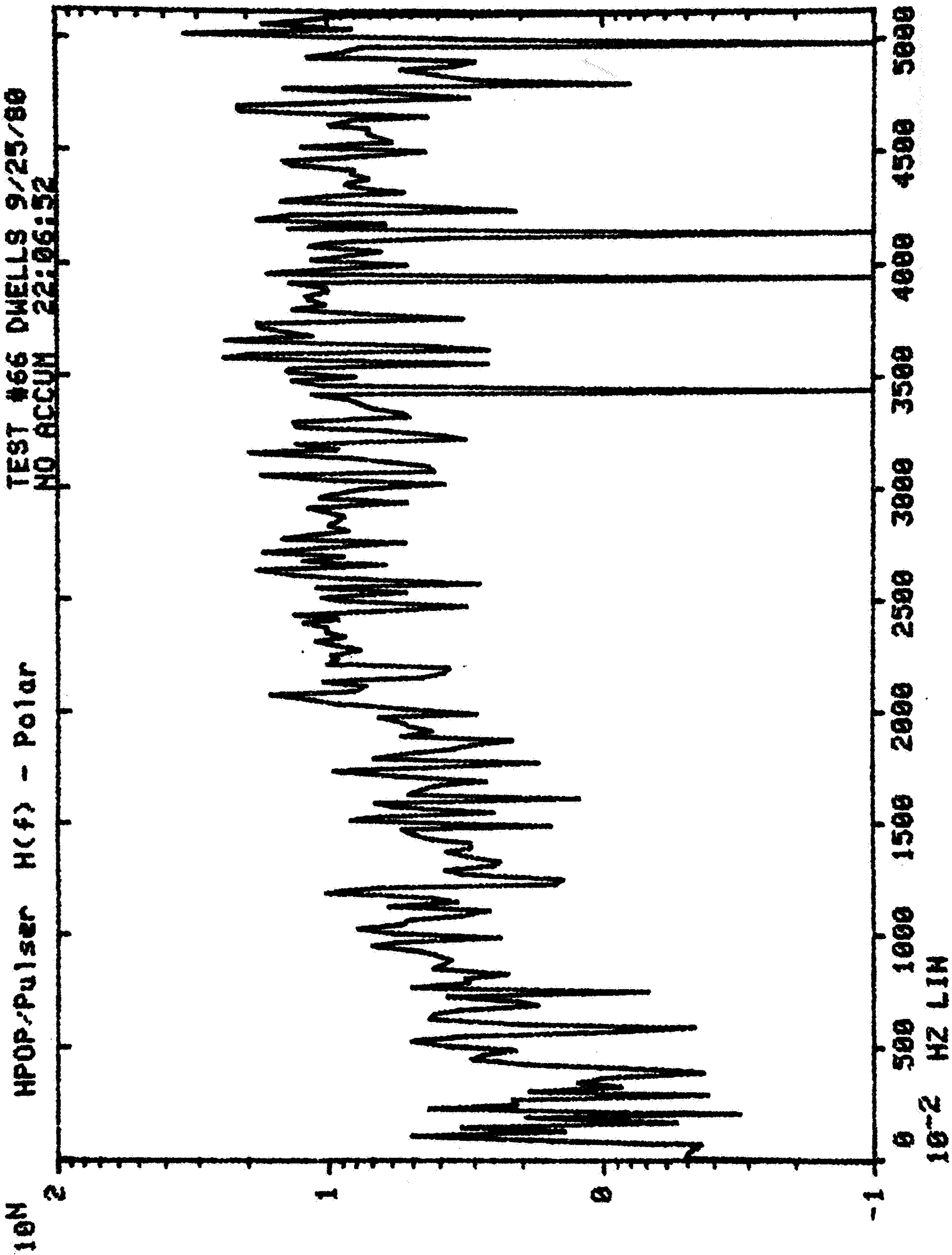

LPOP/Pulser Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

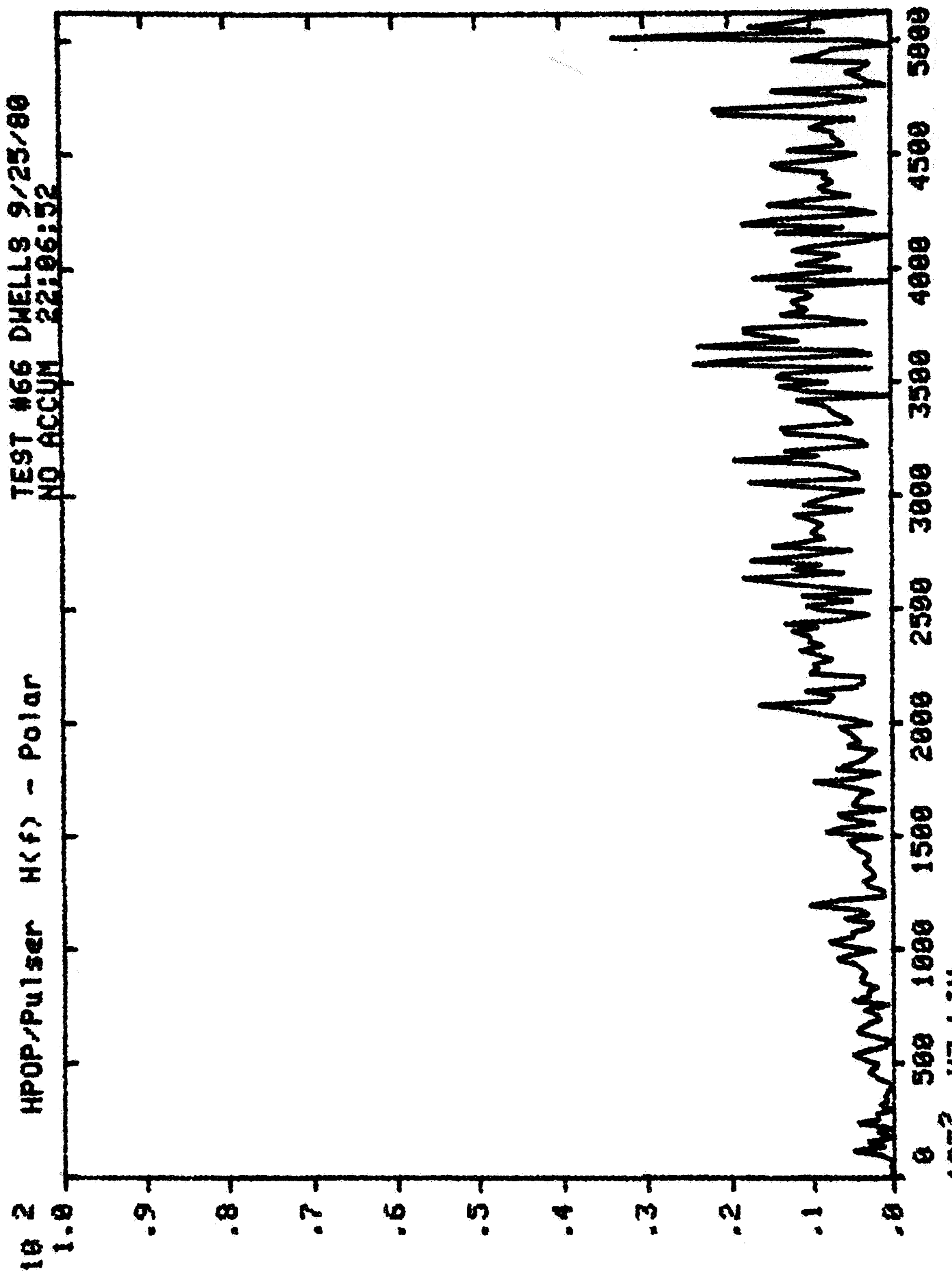

LPDP/Pulser Real XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^{-2} HZ LIN

E34

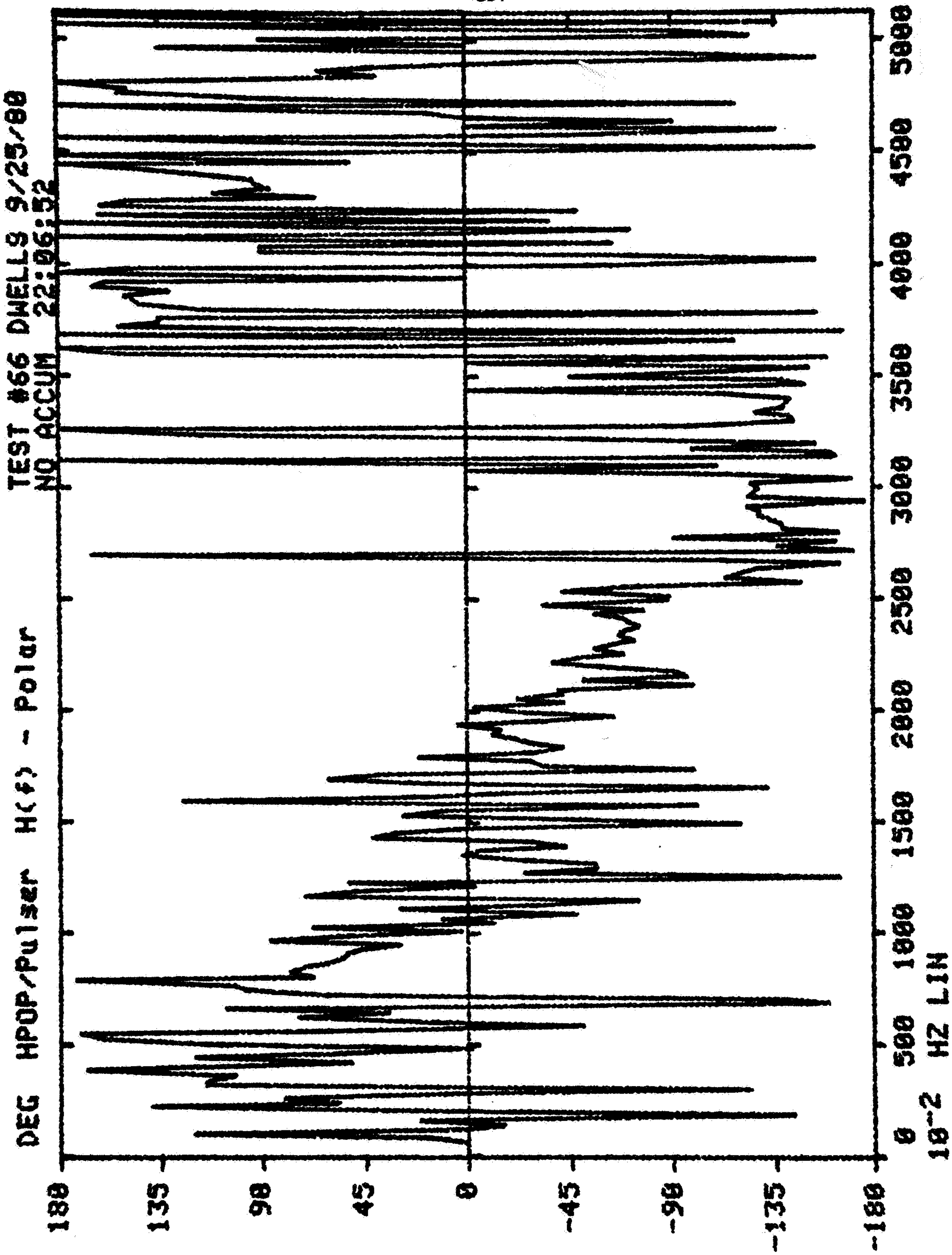


LPDP/Pulser Imag XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
5.0
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
-5.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

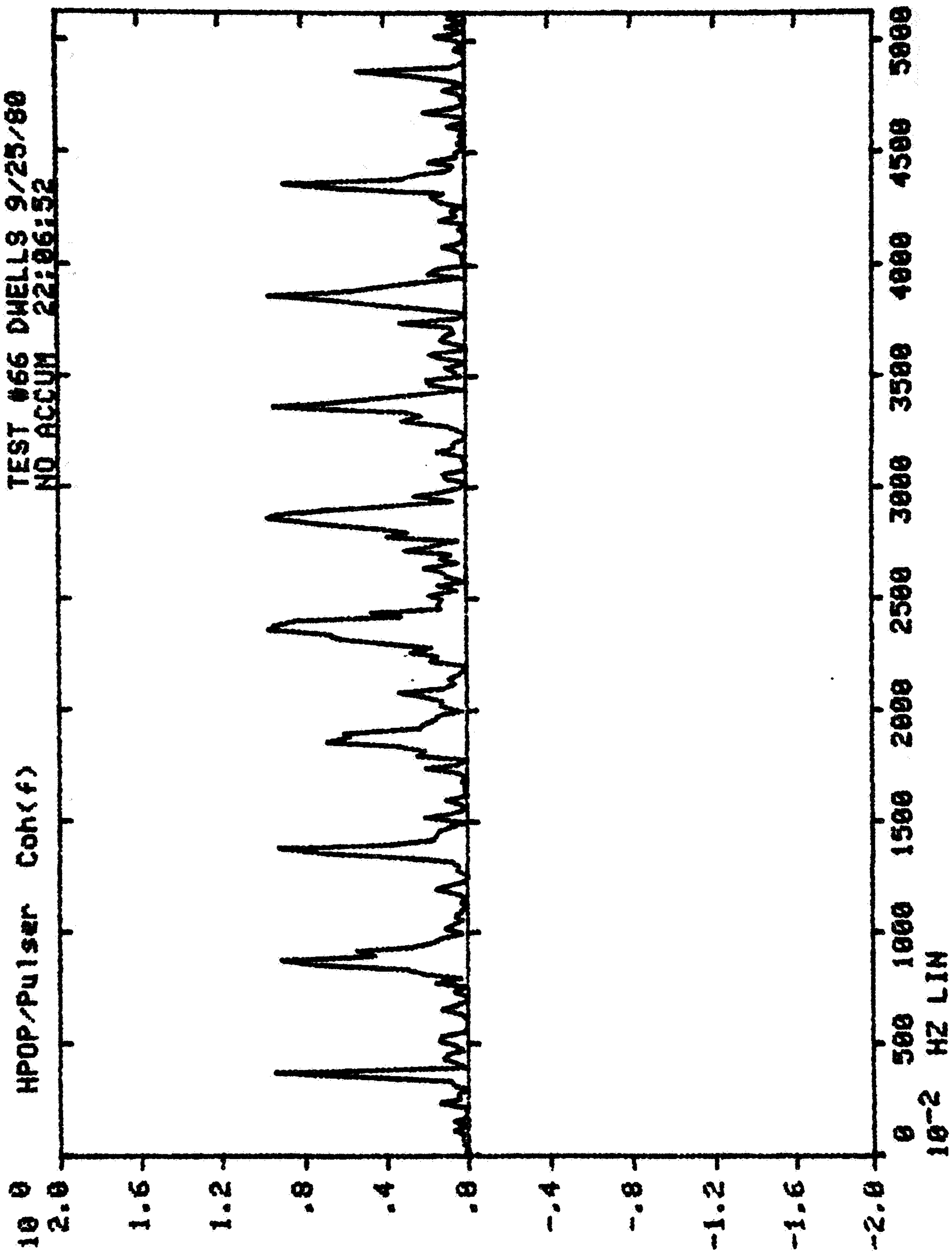

HPOP/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN



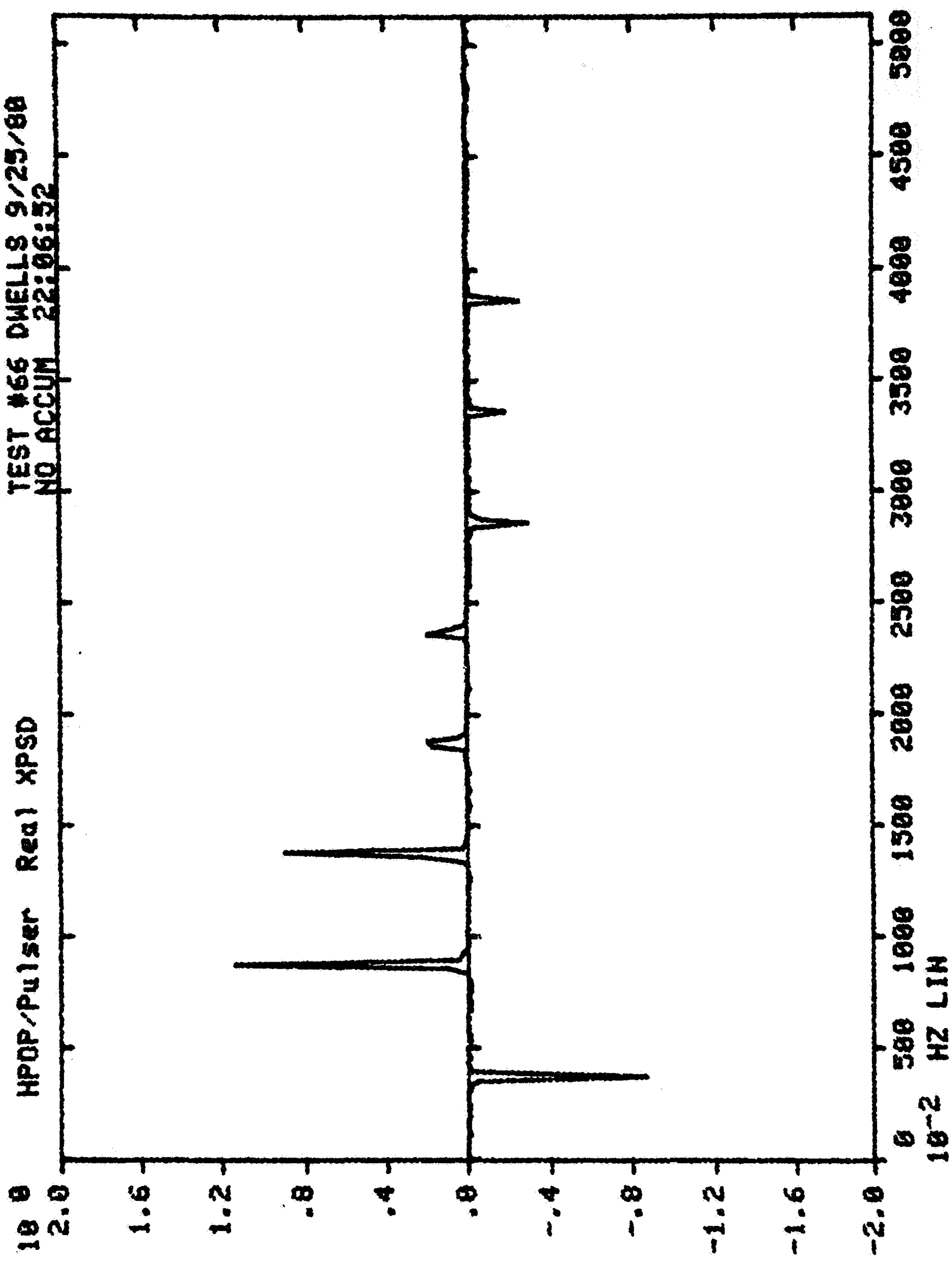
HPOP/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


DEG HPOP/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^2 HZ LIN

E38

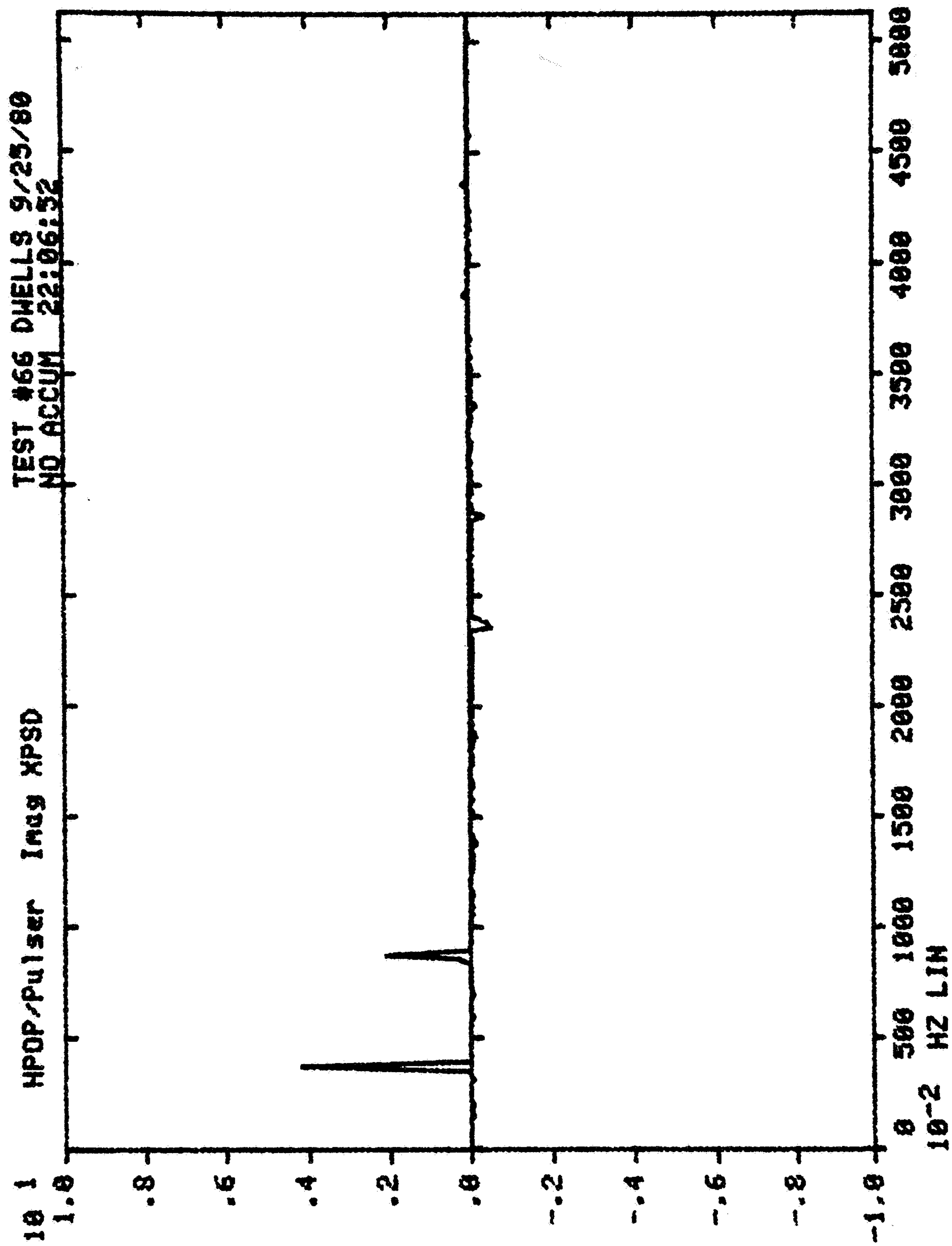


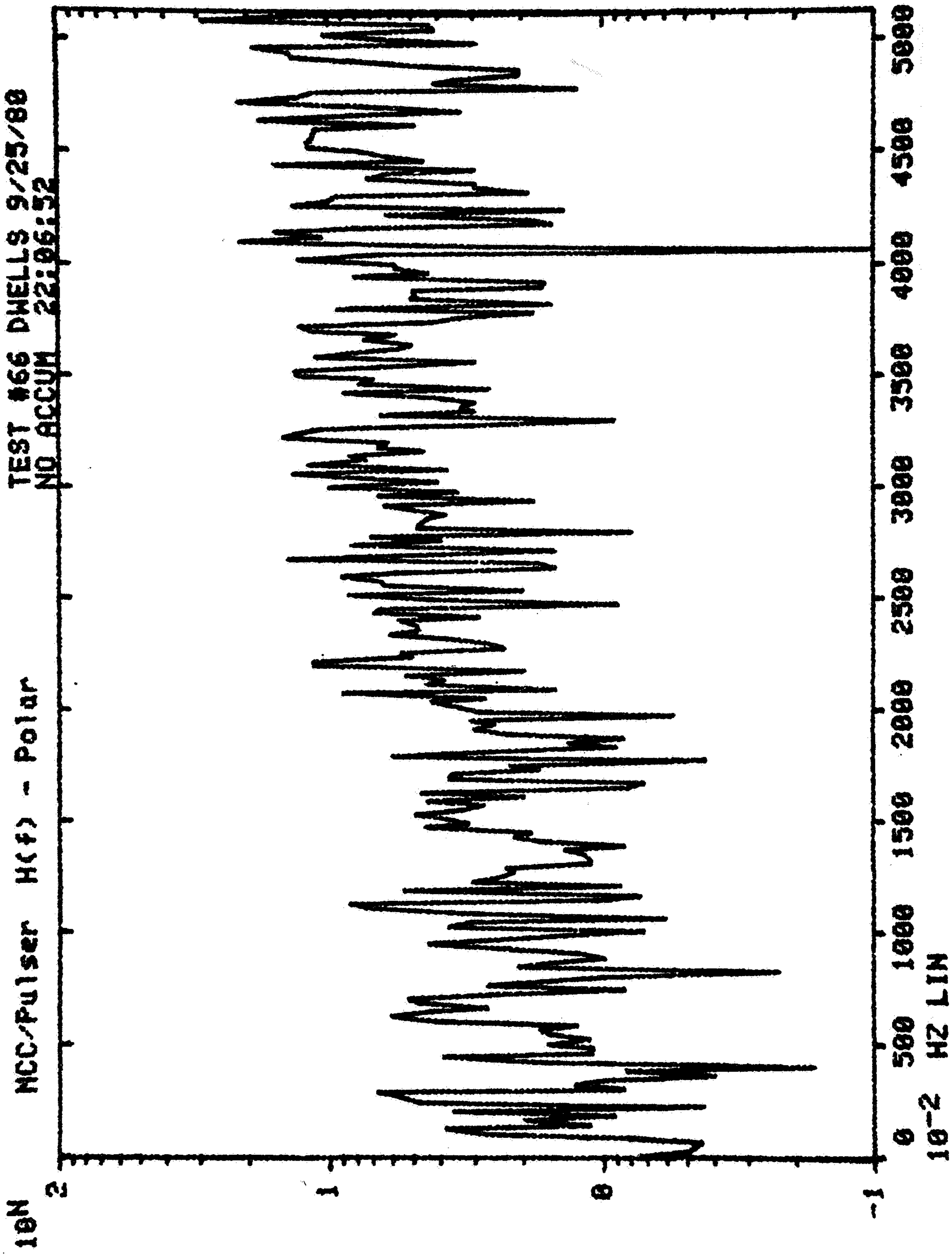
HPOP/Pulser Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN



HPDP/Pulser Real XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

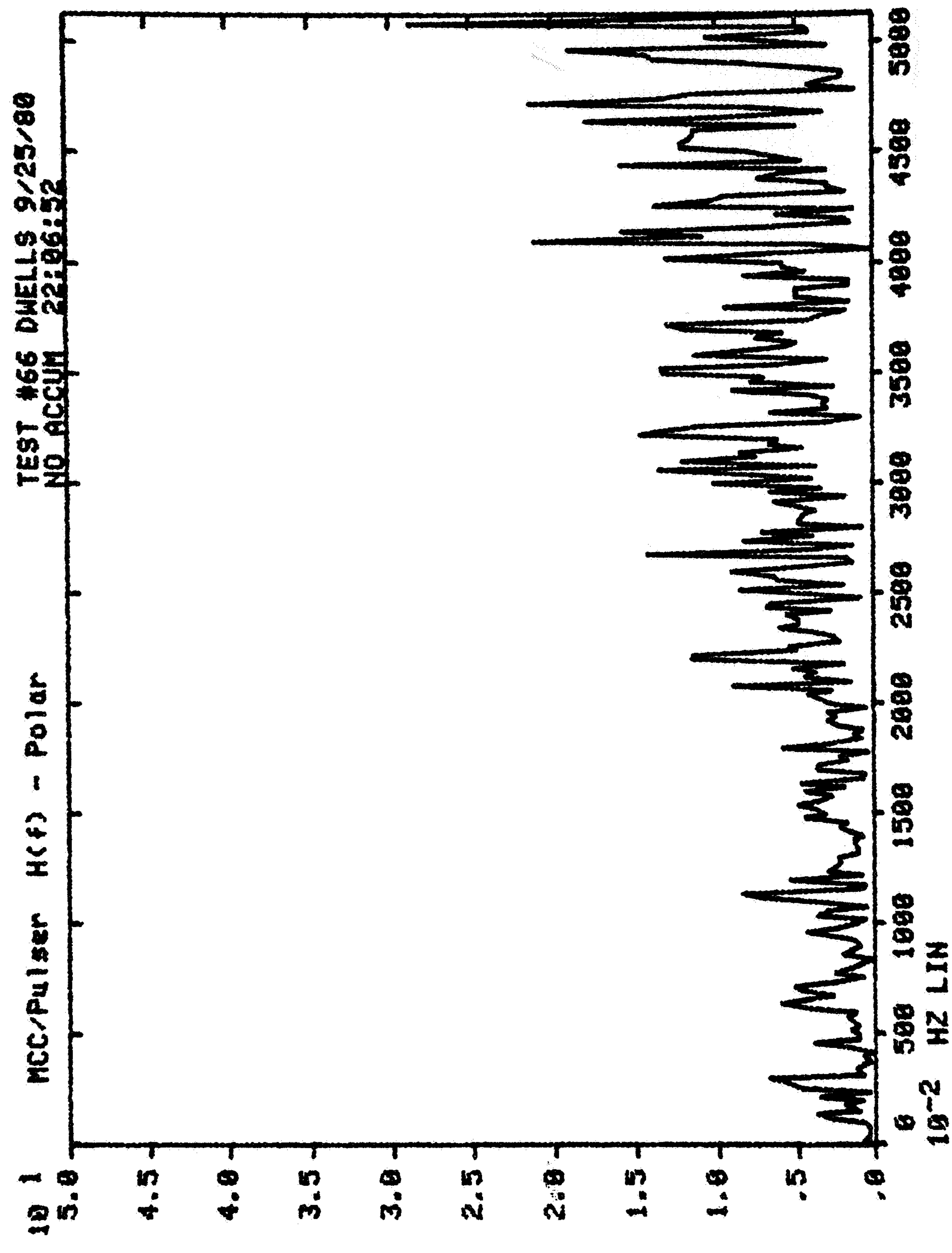
E40


HPDP/Pulser Imag XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

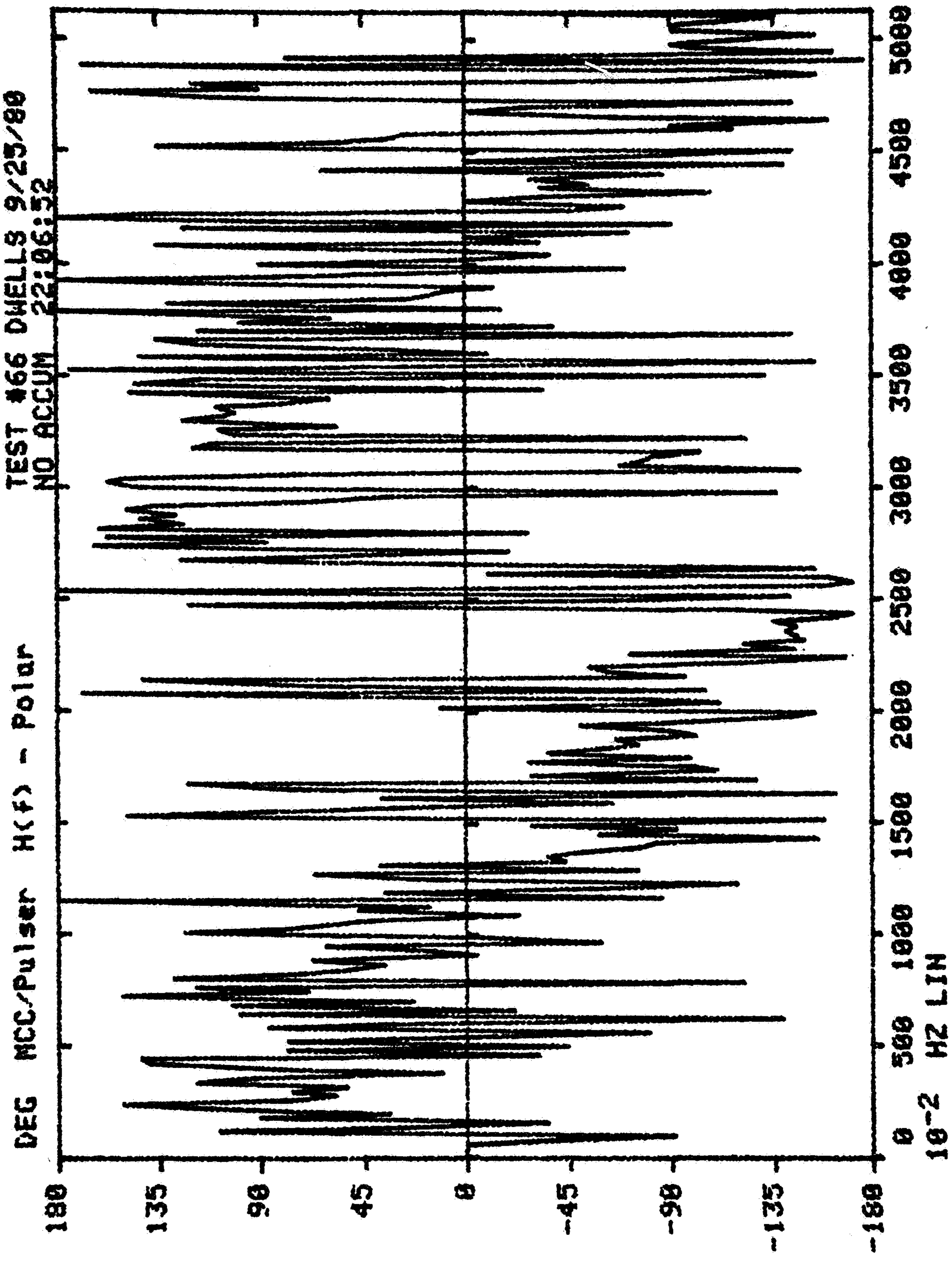


NCC/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/88
NO ACCUM 22:06:52
10N
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2
HZ LIN

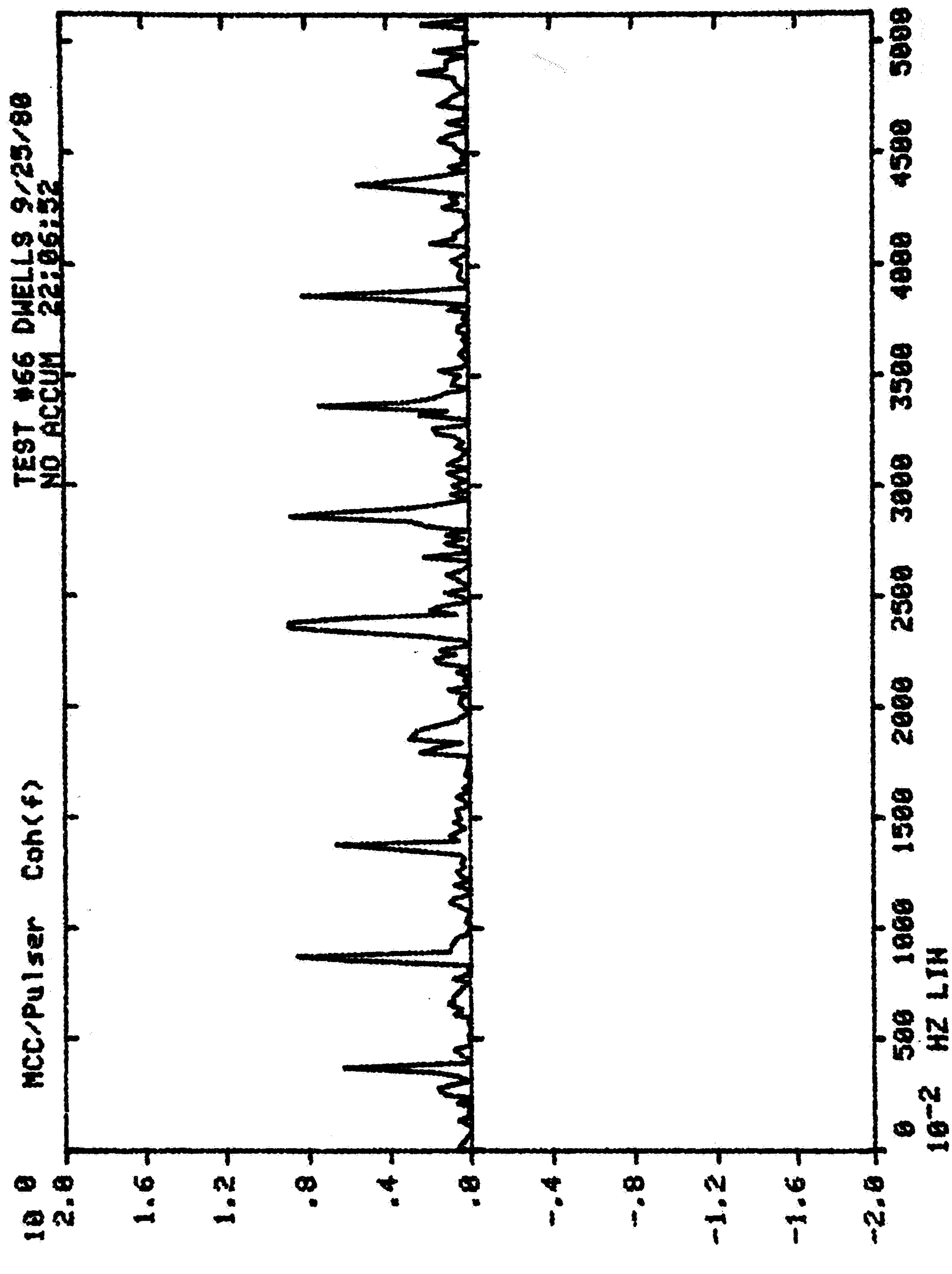
E42



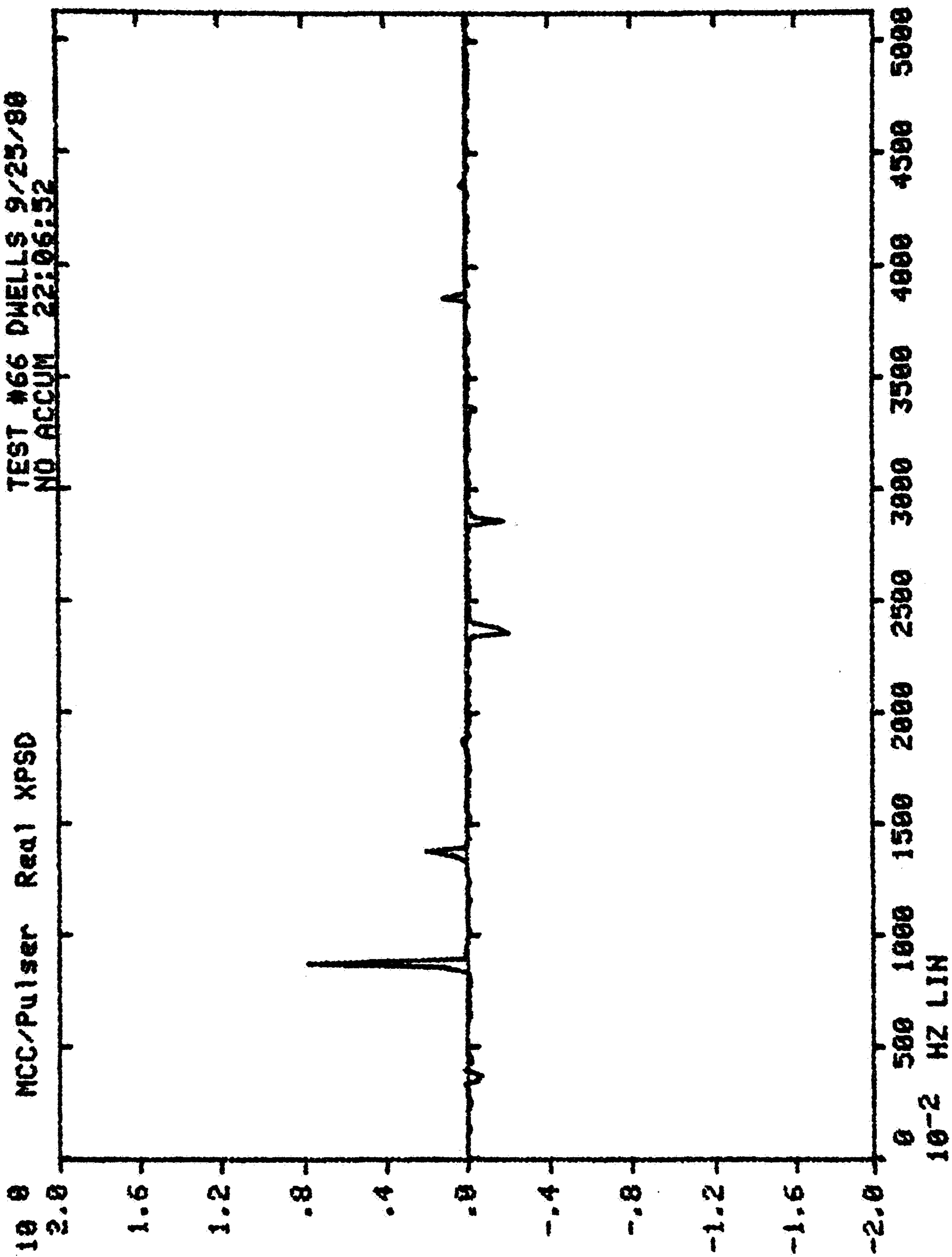
MCC/Pulser H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


DEG MCC/Pulser H(F) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E44

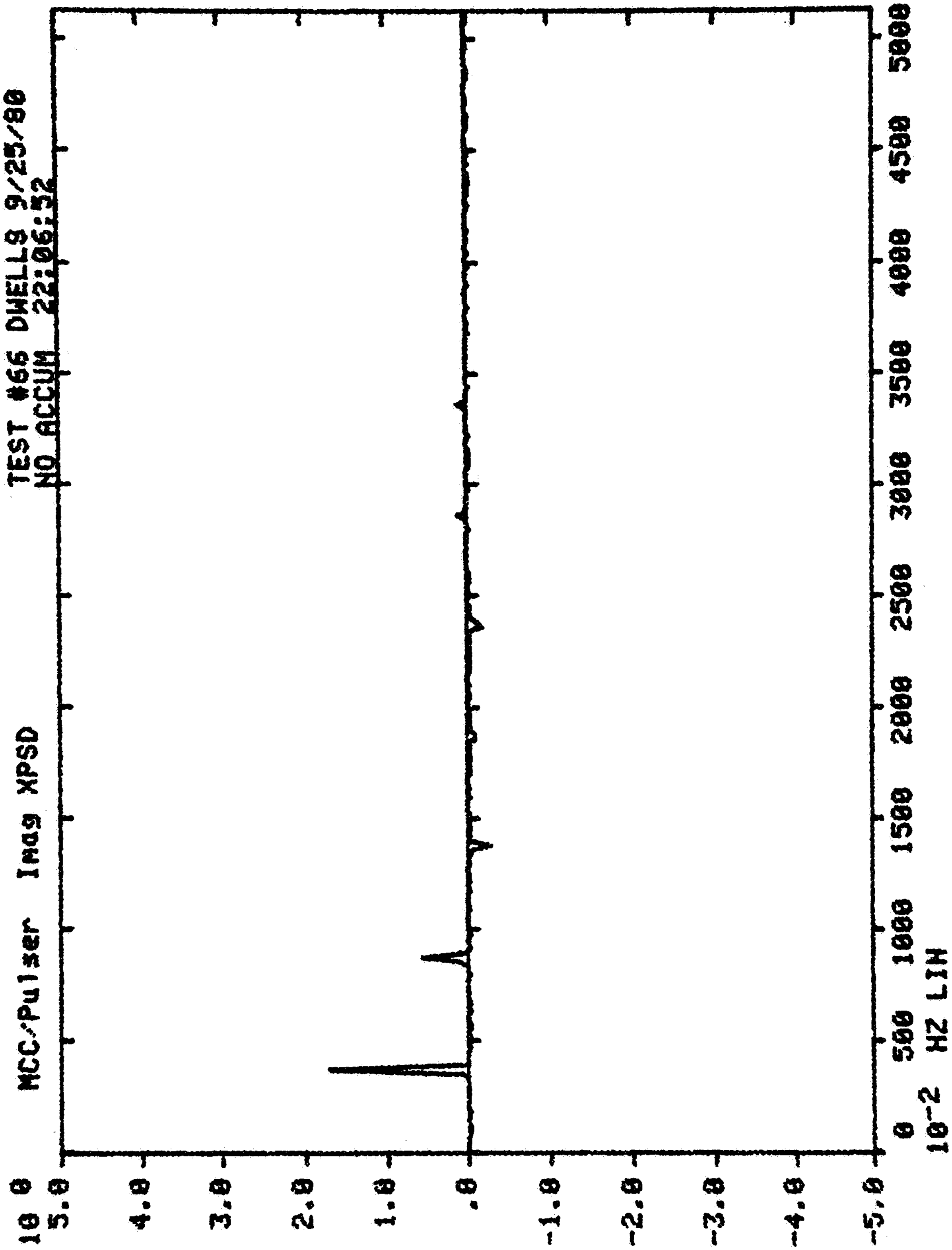

MCC/Pulser Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E45

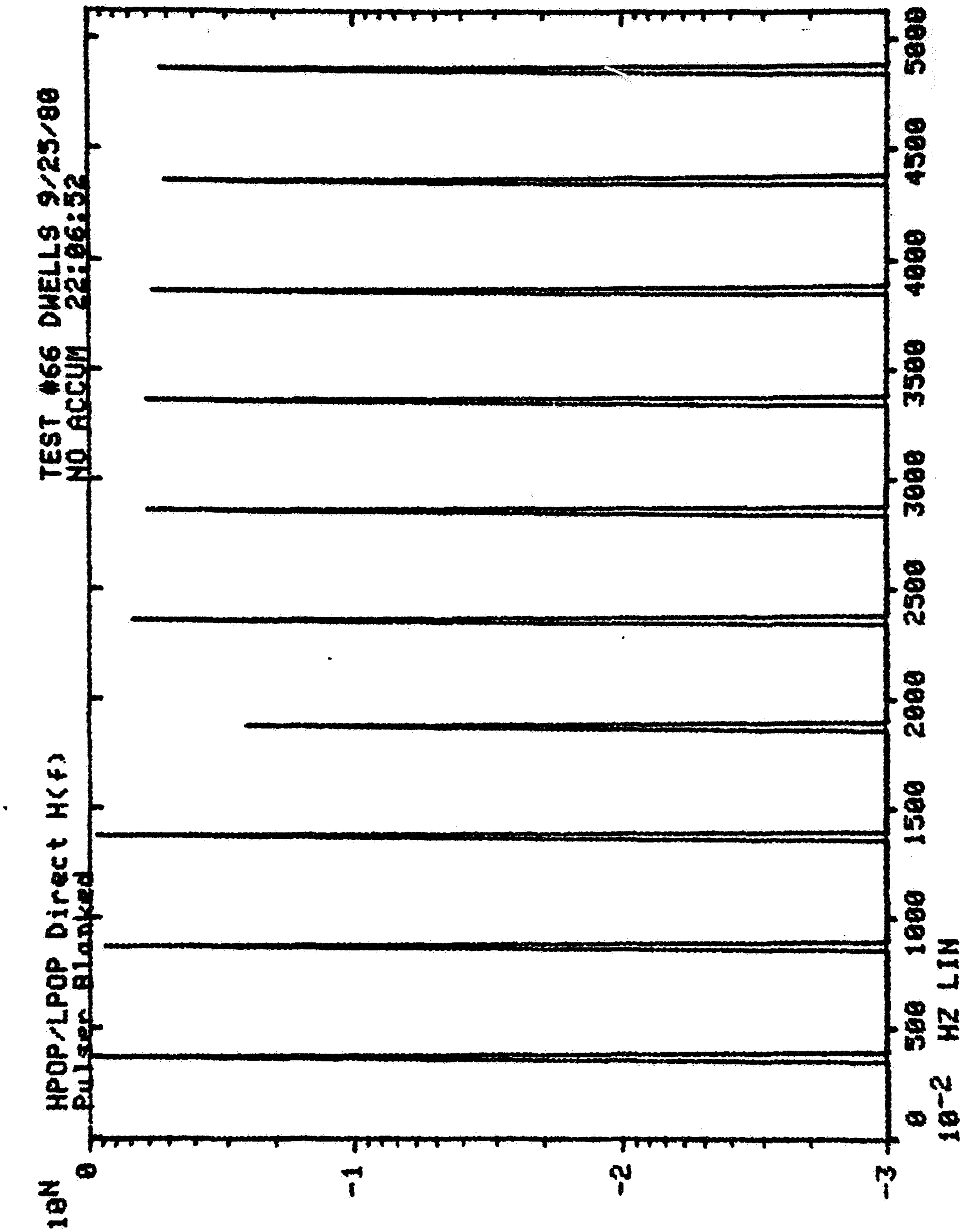


MCC/Pulser Real XPSD
TEST #66 DWELLS 9/25/88
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E46

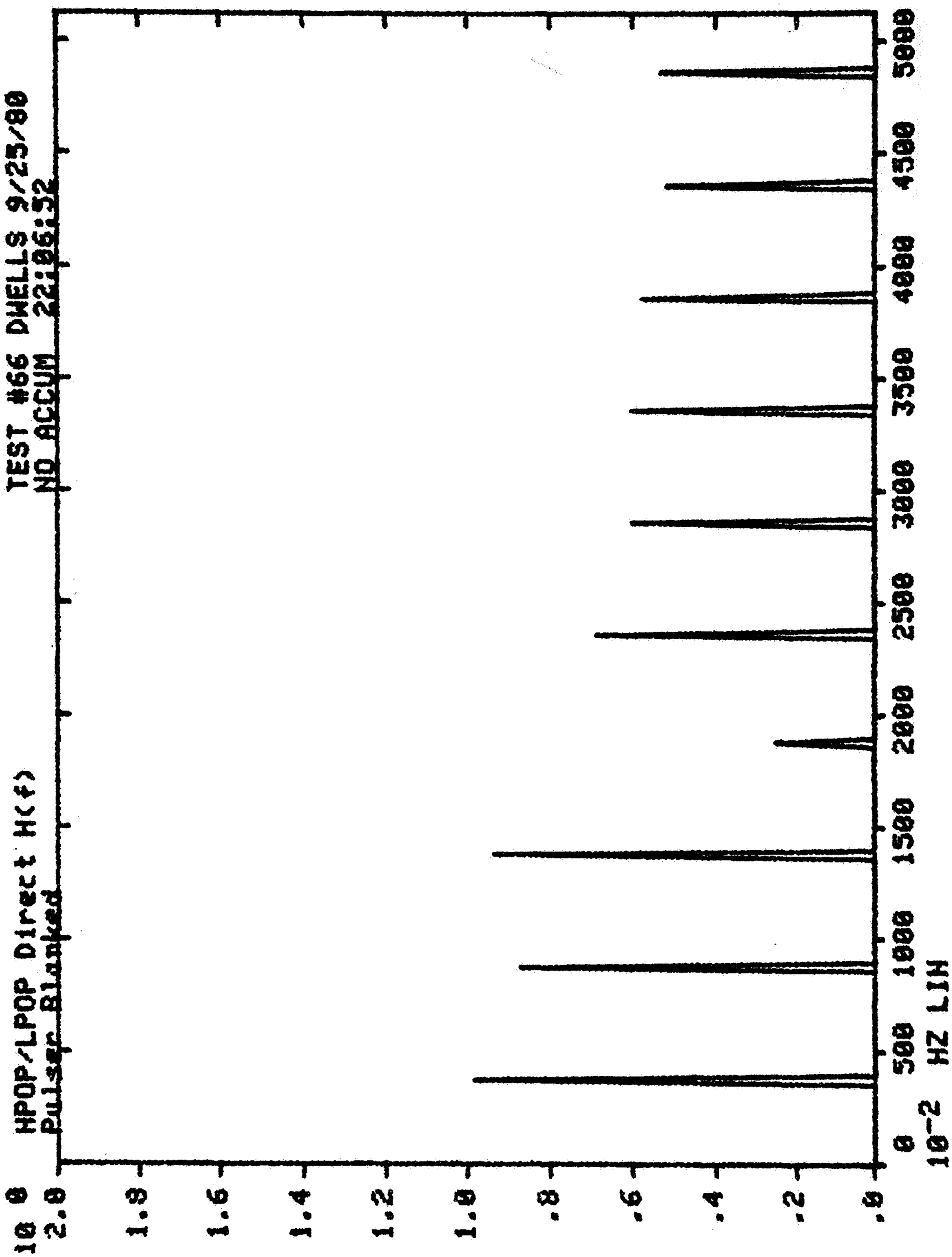


MCC/Pulser Imag XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
5.0
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
-5.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2
HZ LIN

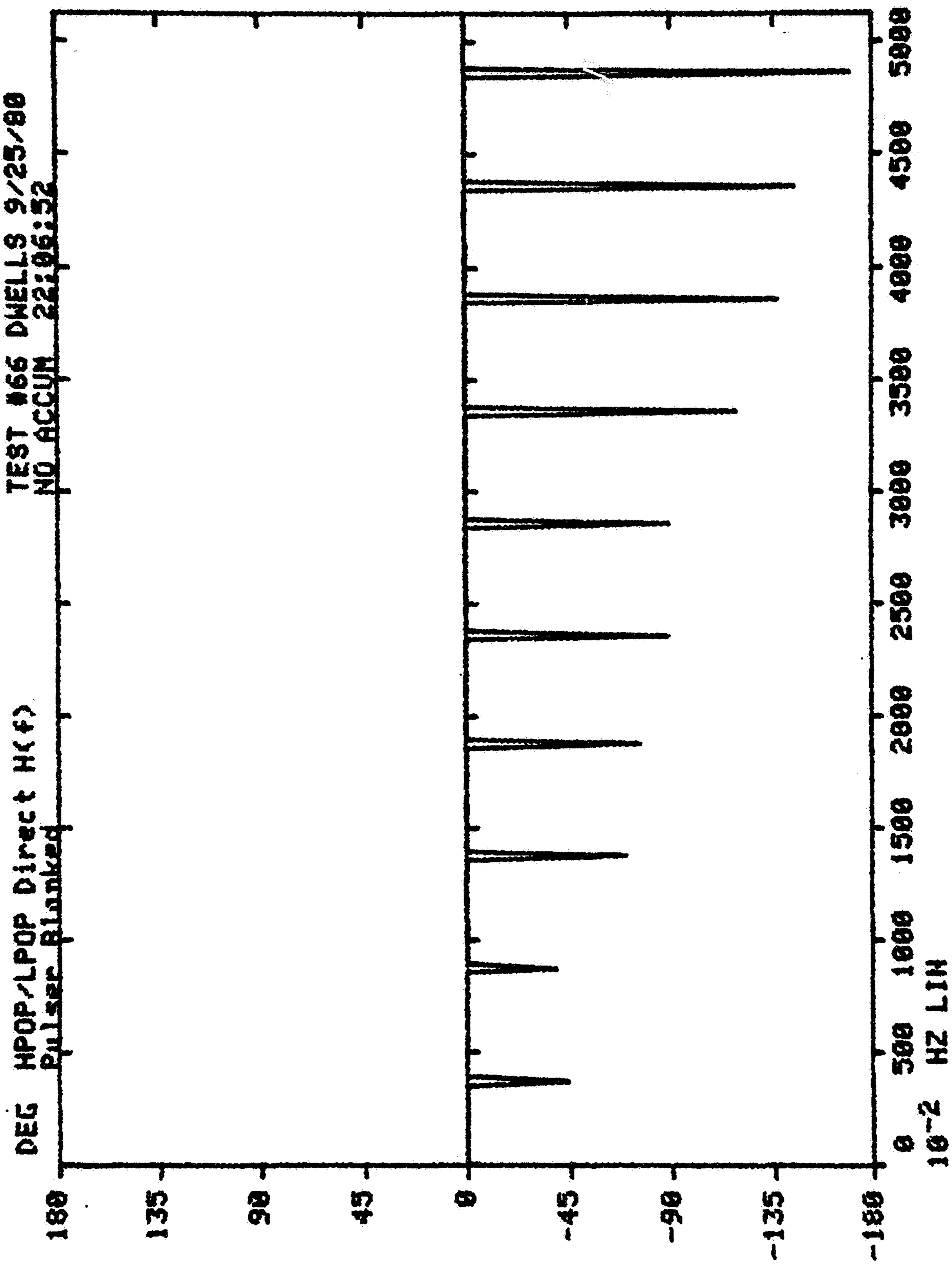


HPOP/LPOP Direct H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
0
-1
-2
-3
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

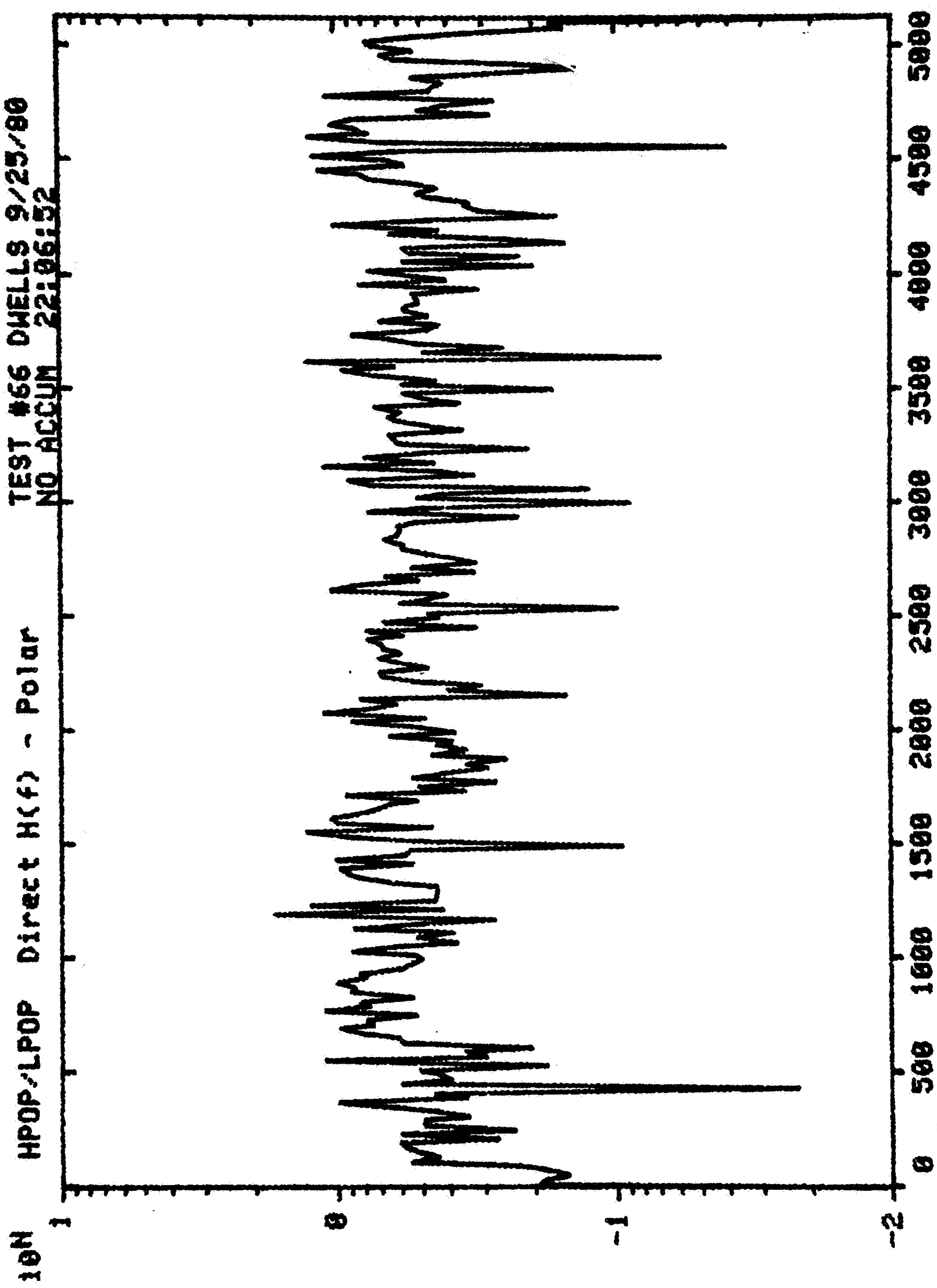
E48



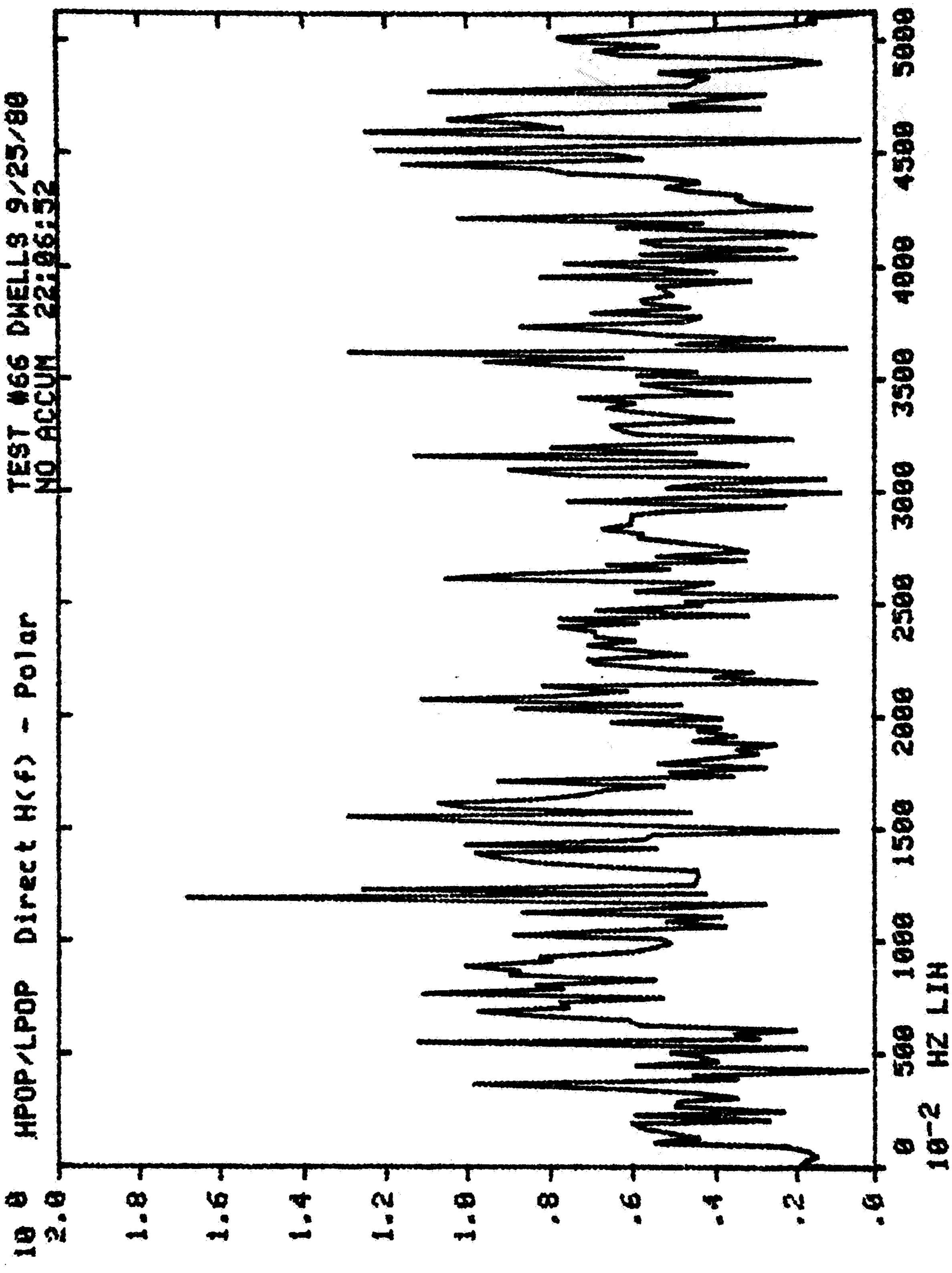
HPOP/LPOP Direct H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


DEG
HPOP/LPOP Direct H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E50

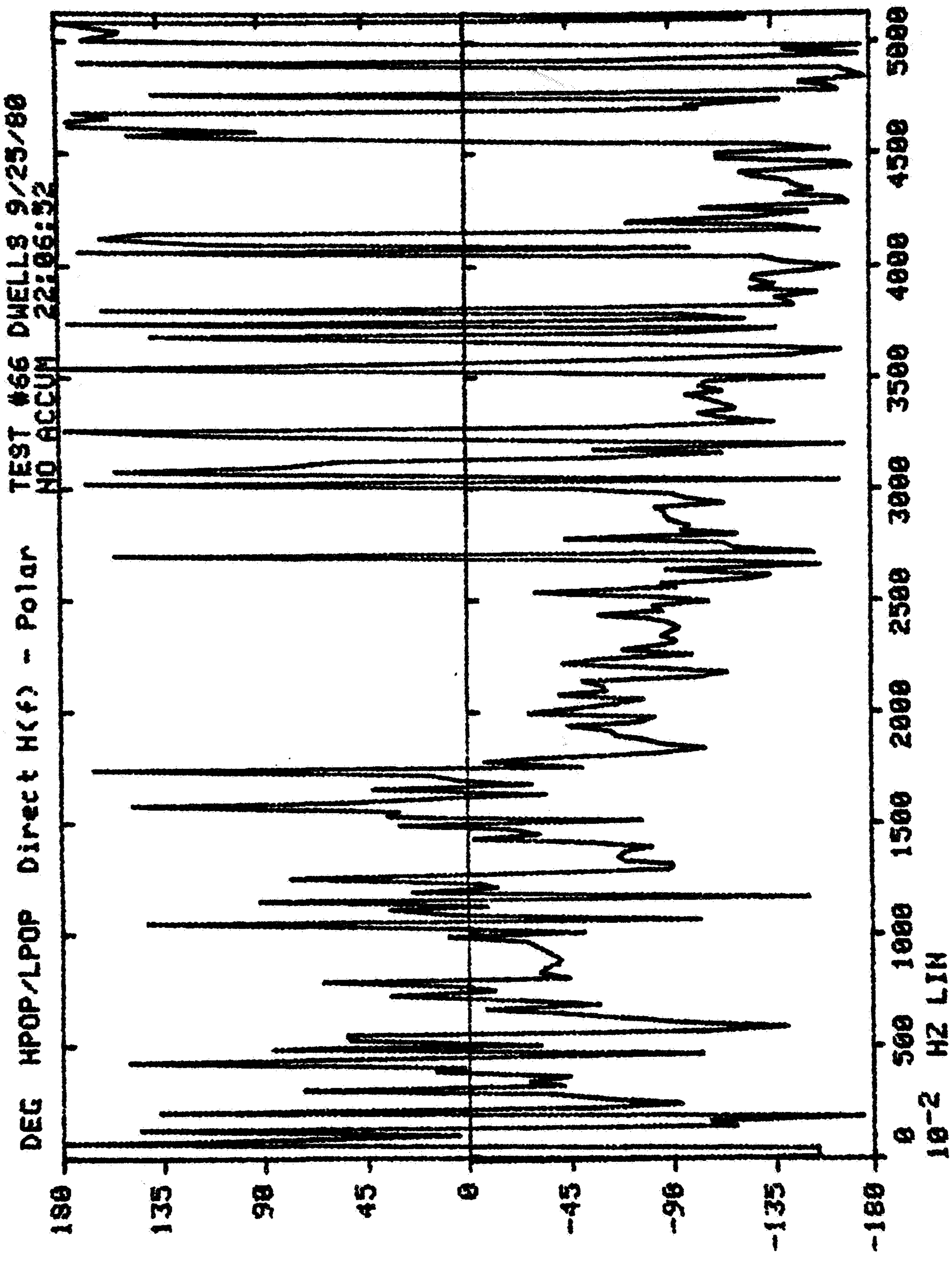


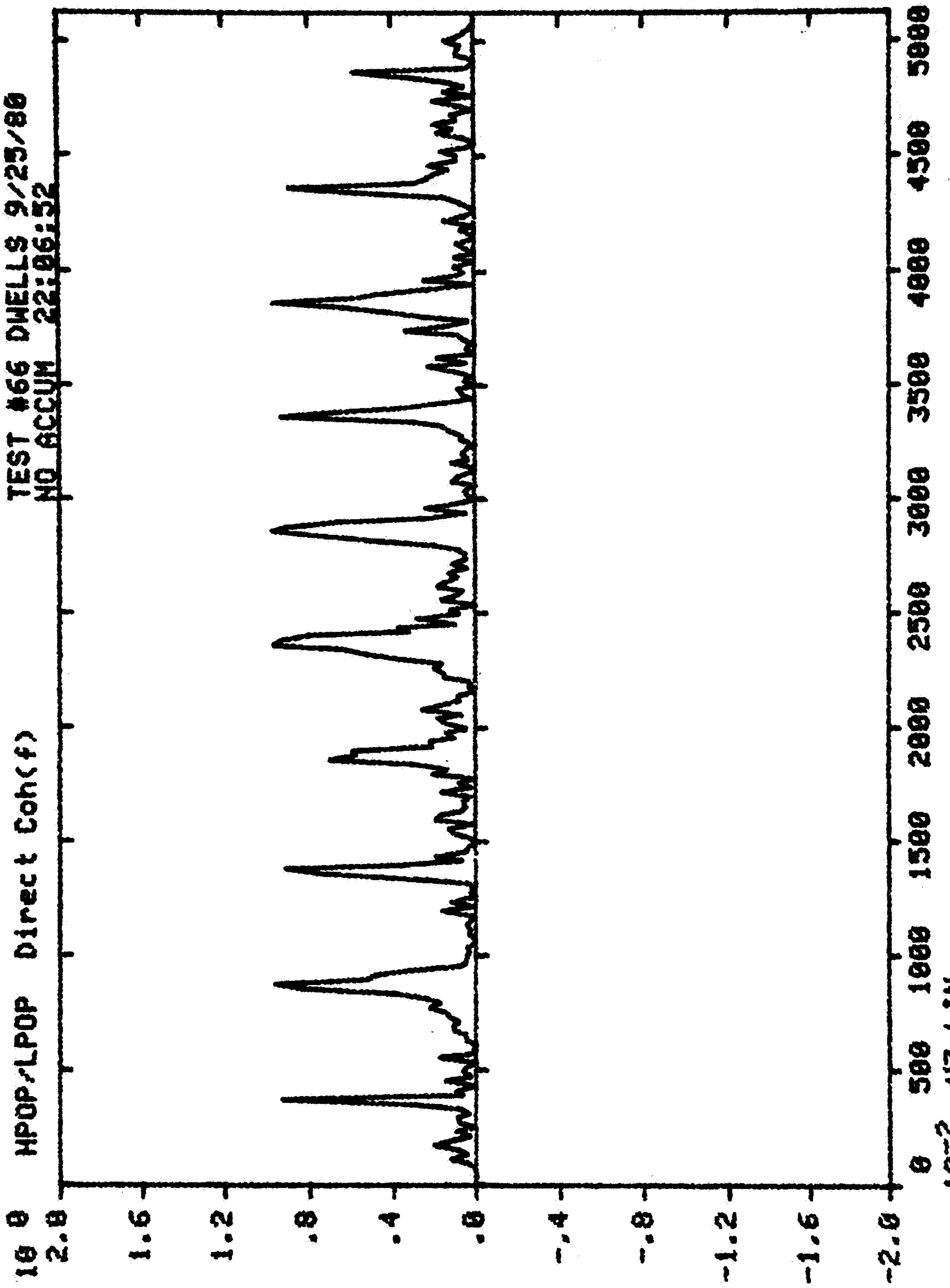
HPOP/LPOP Direct H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN



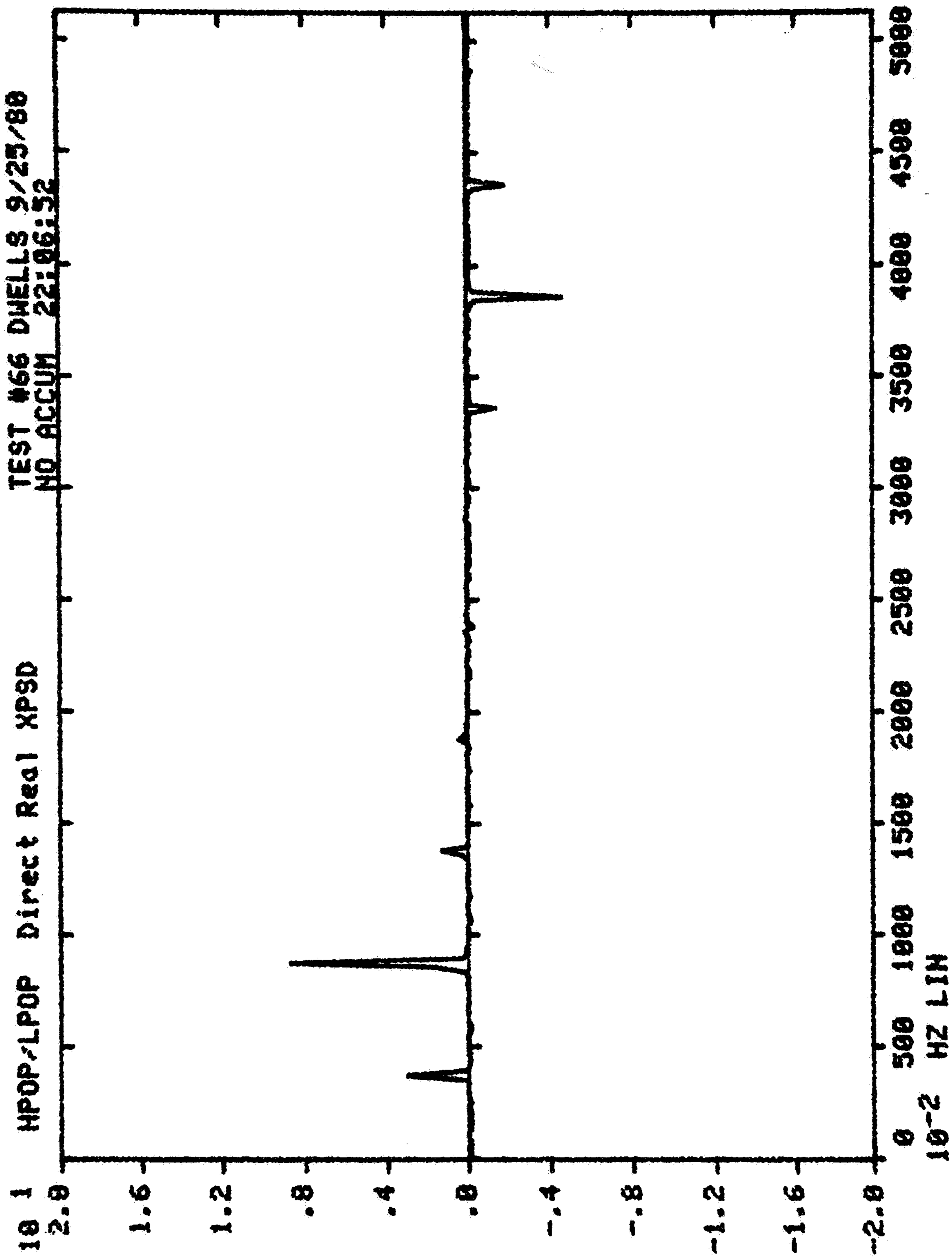
HPOP/LPOP Direct H(F) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E52

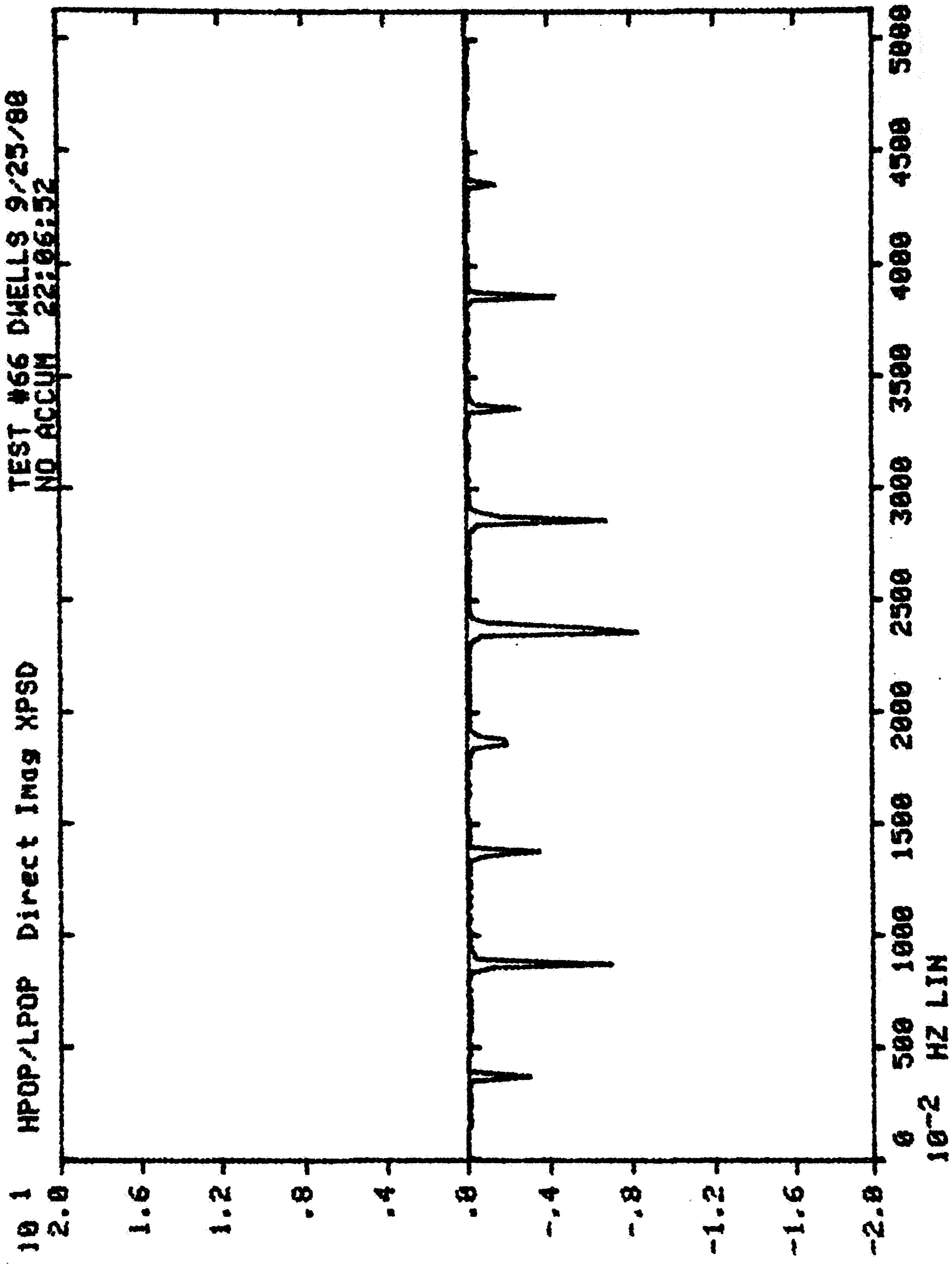

DEG HPOP/LPOP Direct H(f) - Polar TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:32
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


HPOP/LPOP Direct Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E54

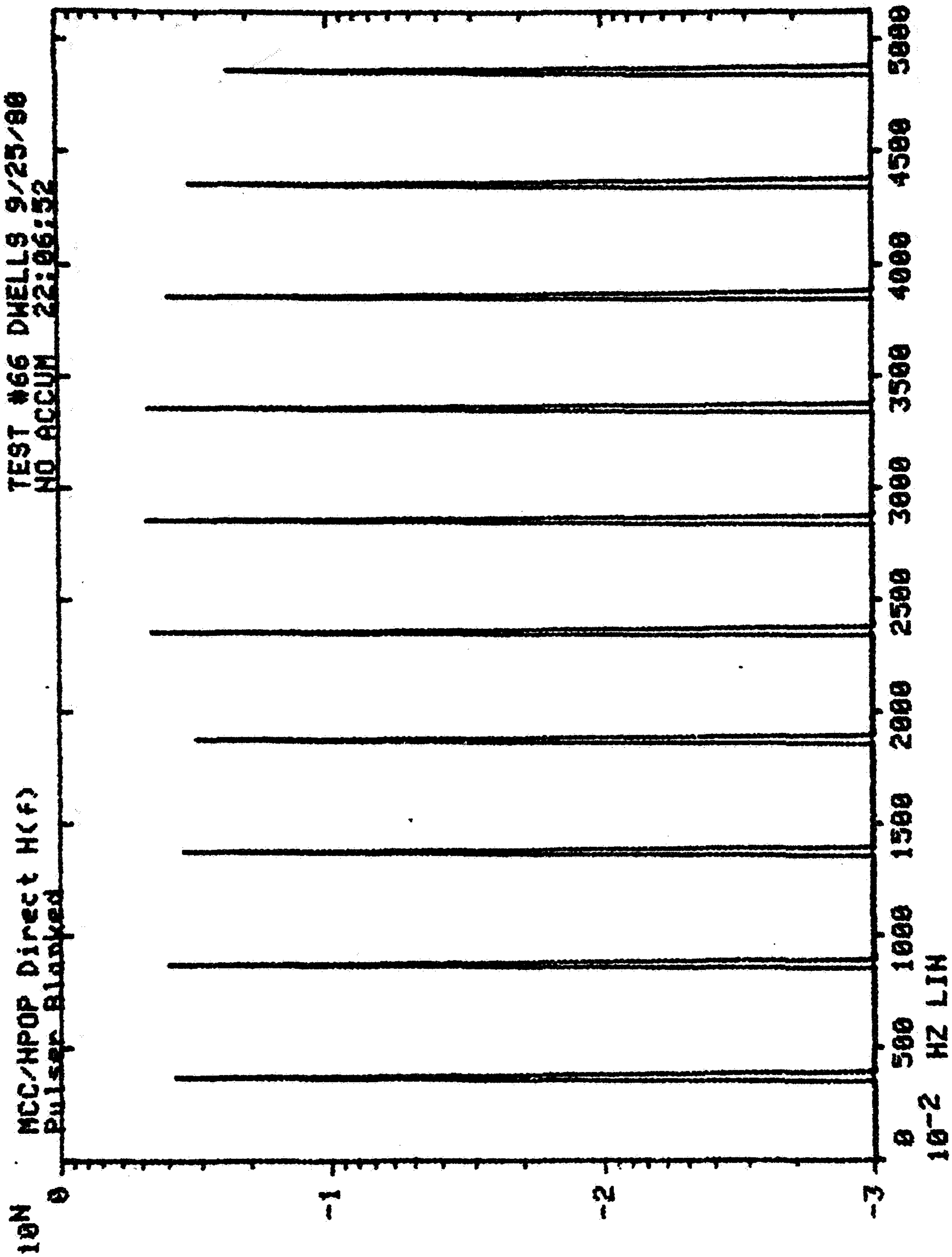


HPOP/LPOP Direct Real XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN



HPOP/LPOP Direct Imag XPSD
TEST #66 DWELLS 9/25/88
NO ACCUM 22:06:52
10 1
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2
HZ LIN

E56



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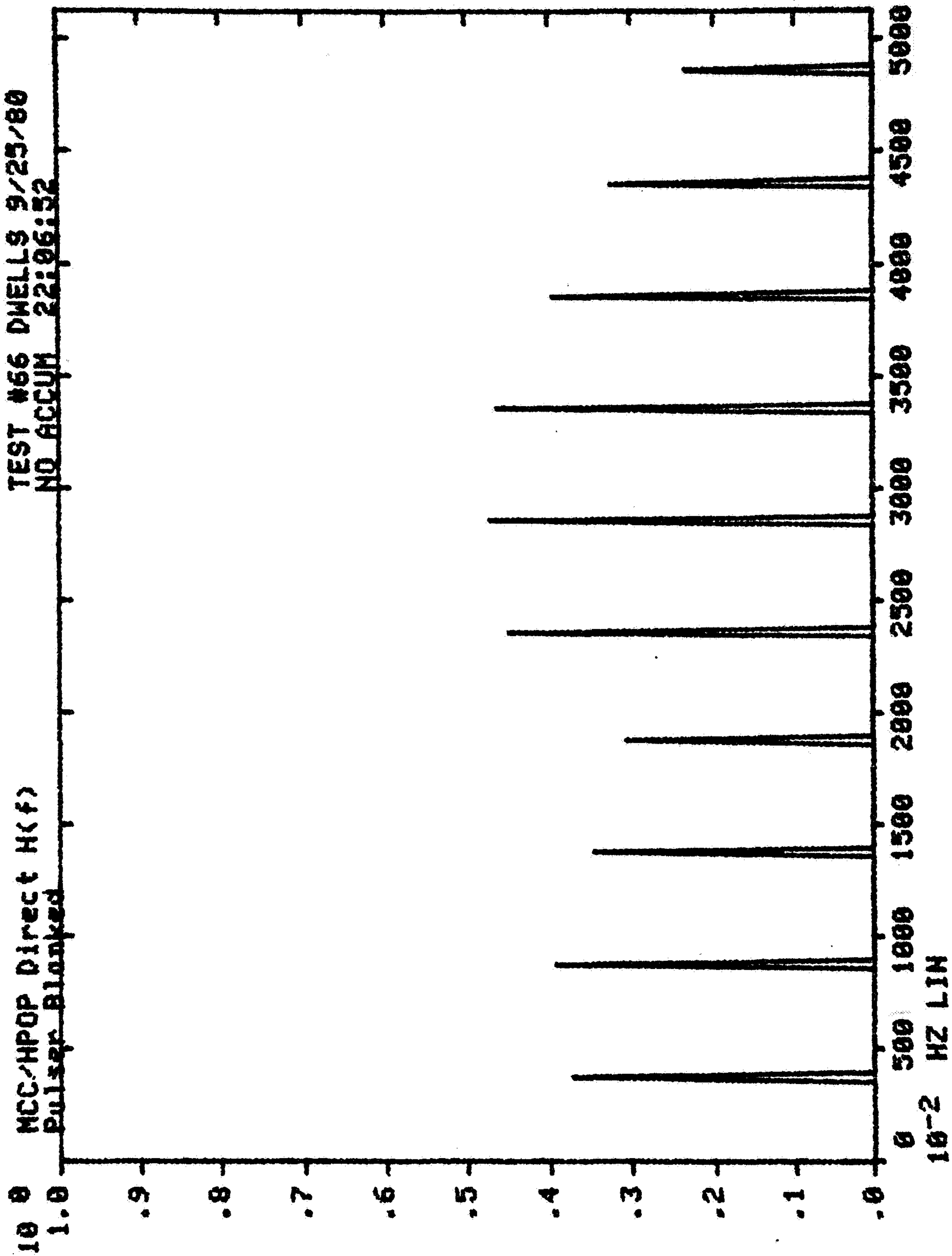
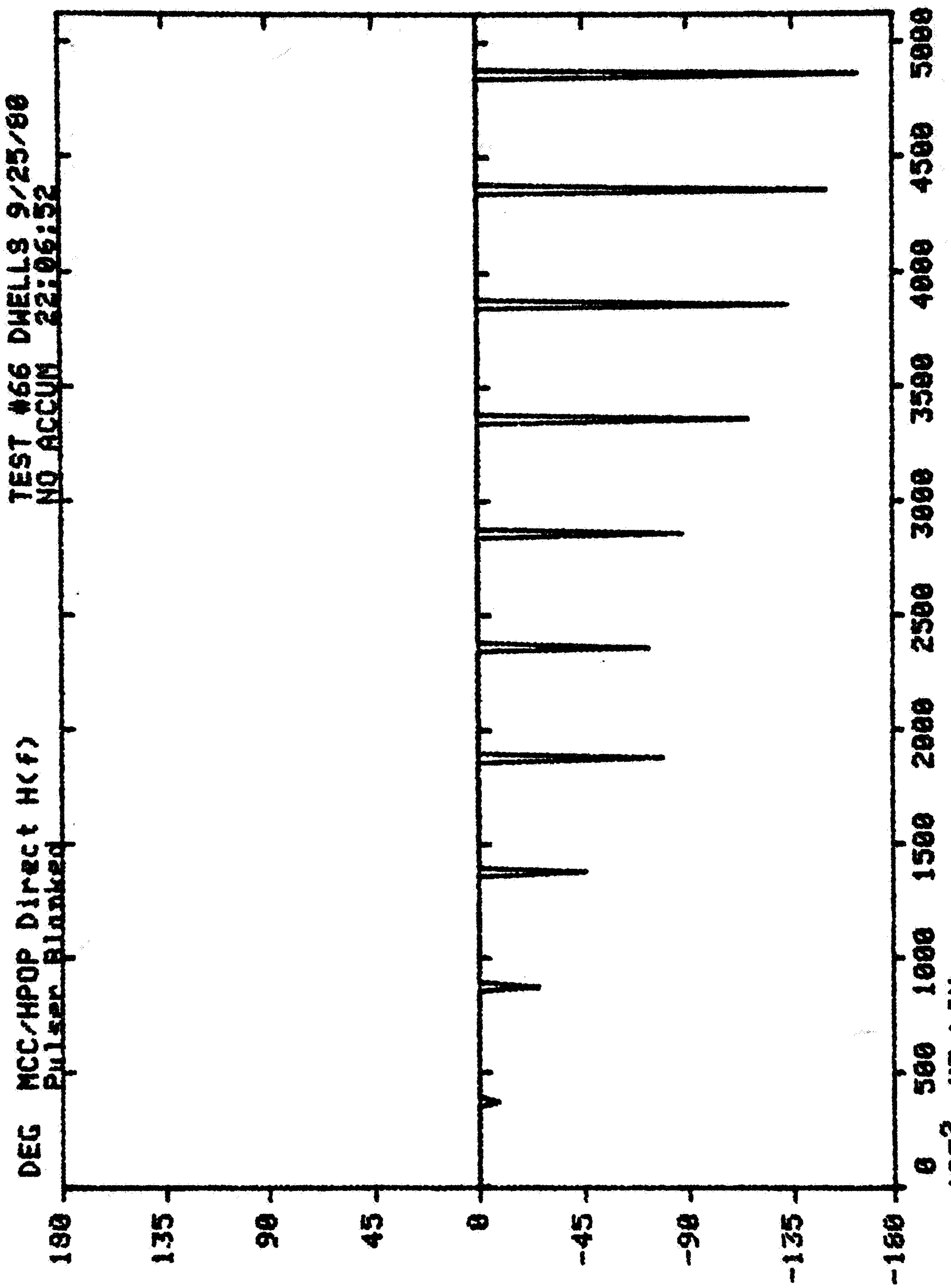
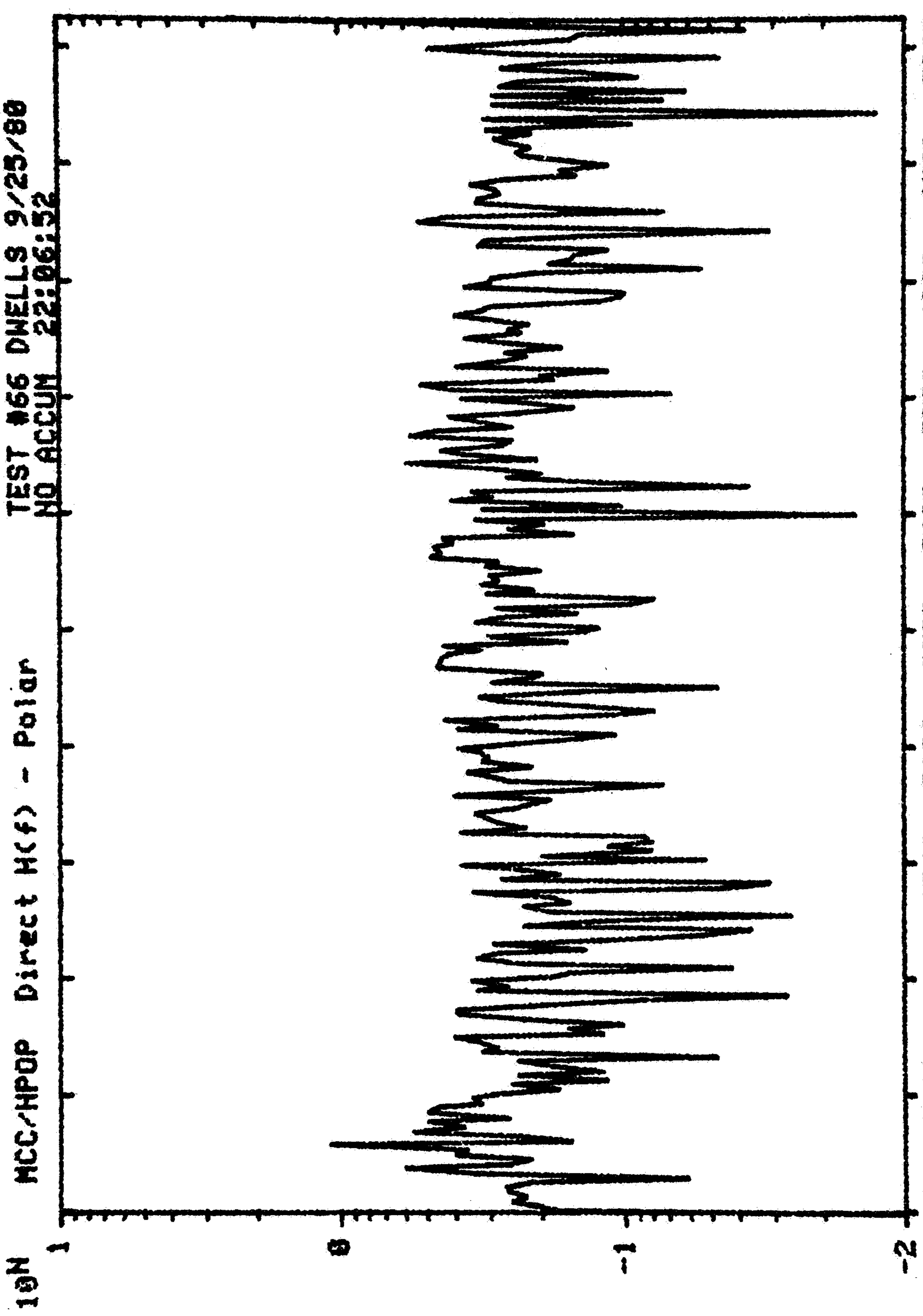
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
0
-1
-2
-3
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

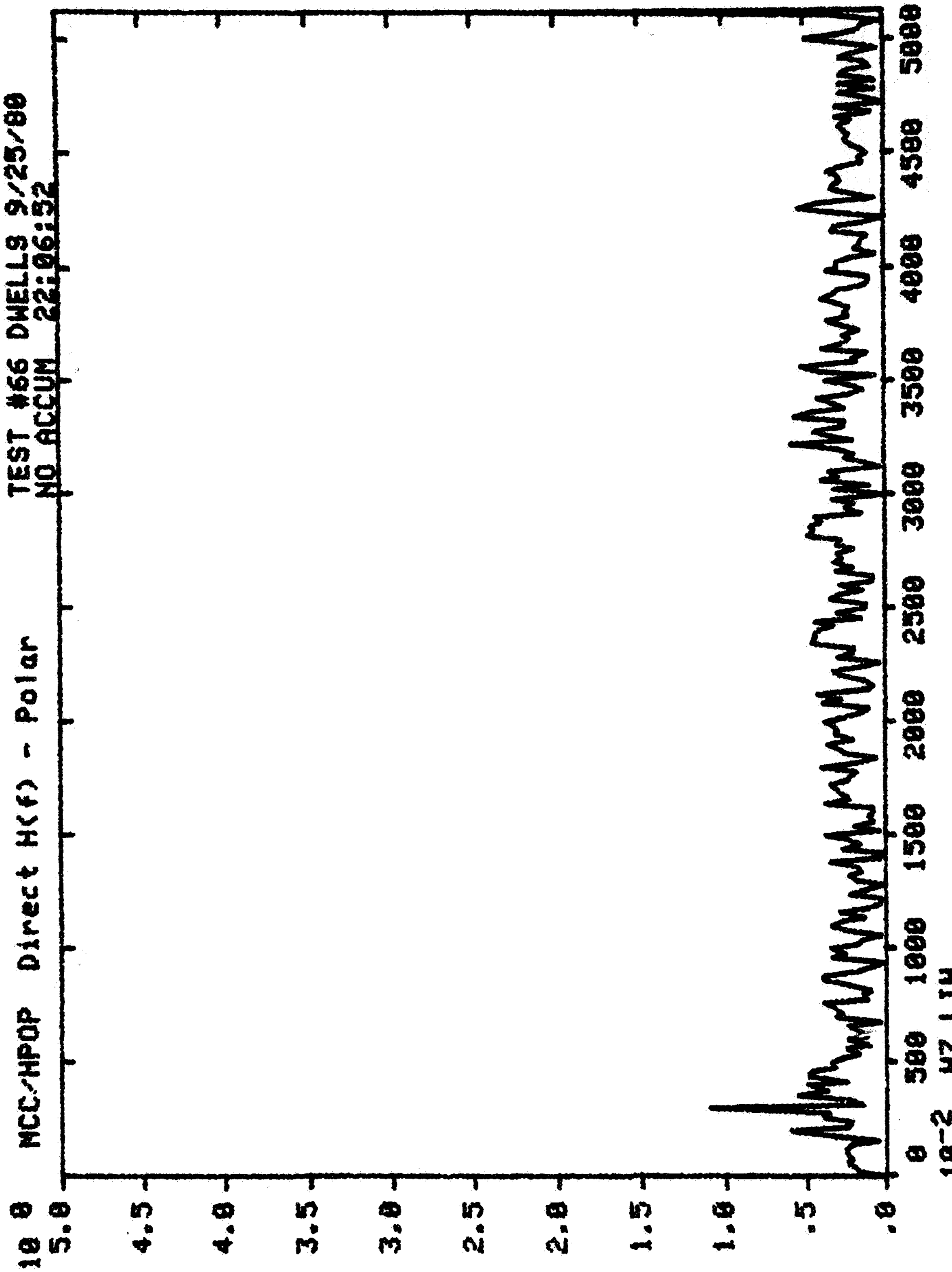

MCC/HPOP Direct H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E58

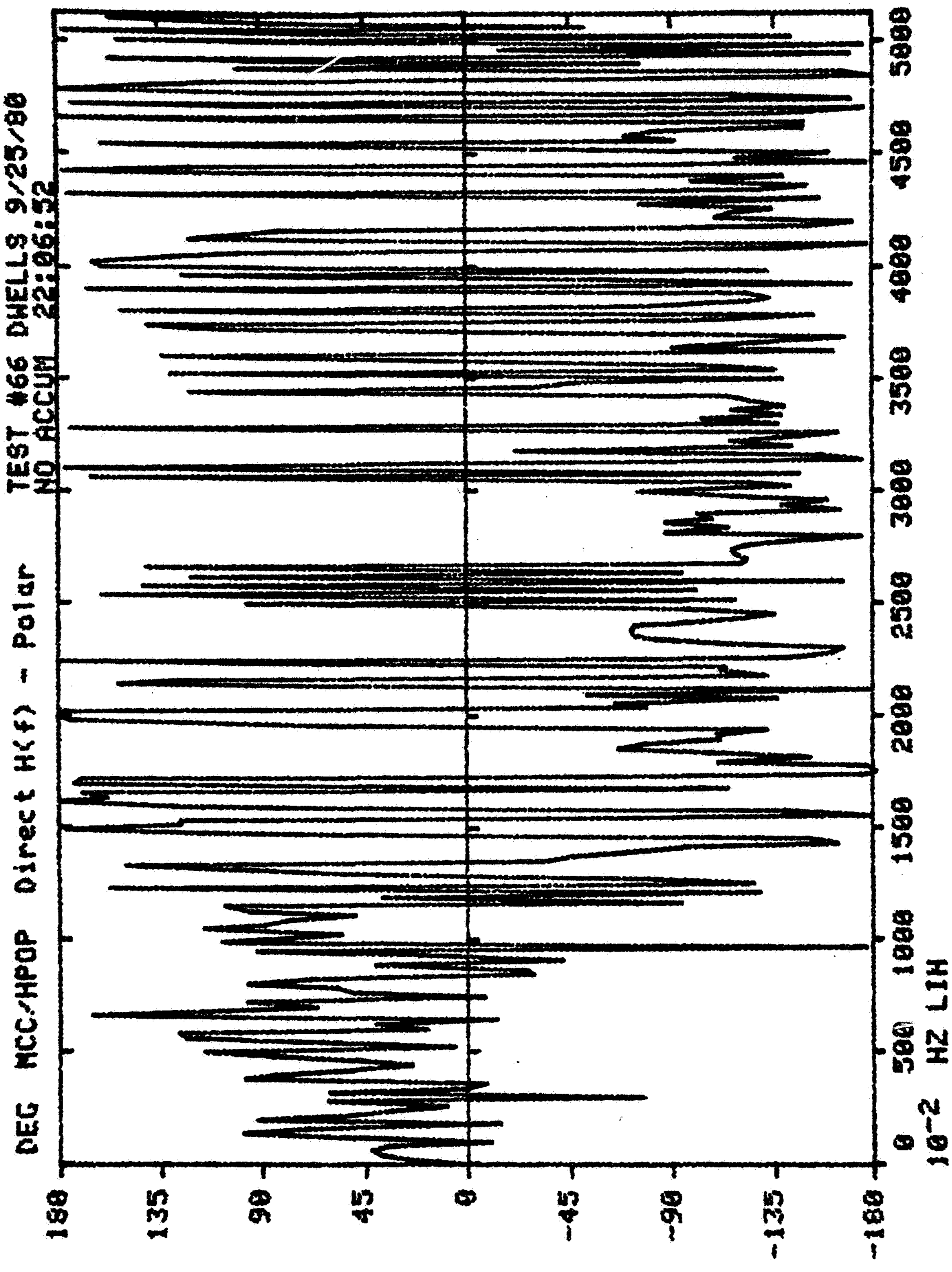


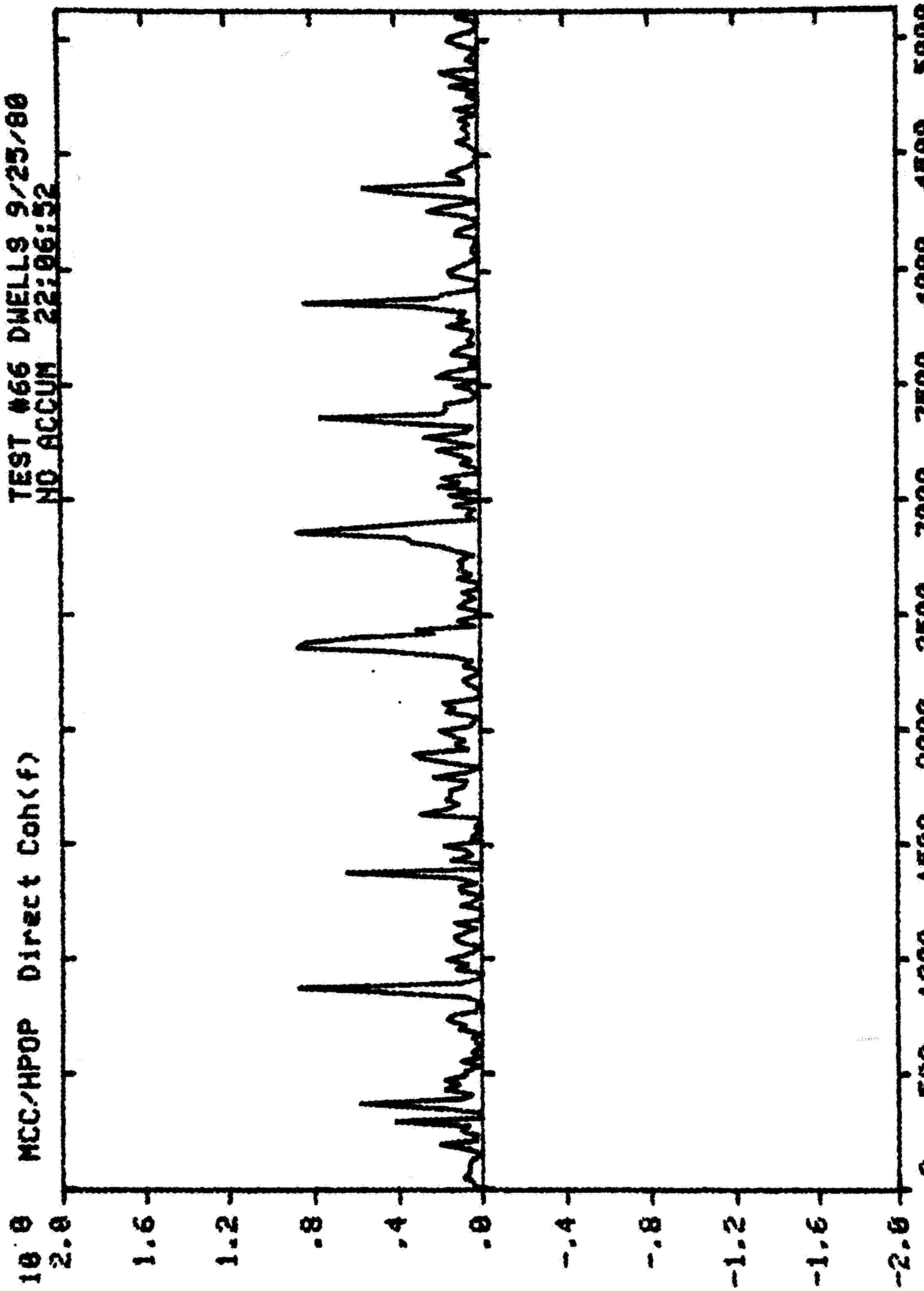
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
MCC/HPOP Direct H(f)
Pulser Blanked
DEG
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


MCC/HPDP Direct H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN



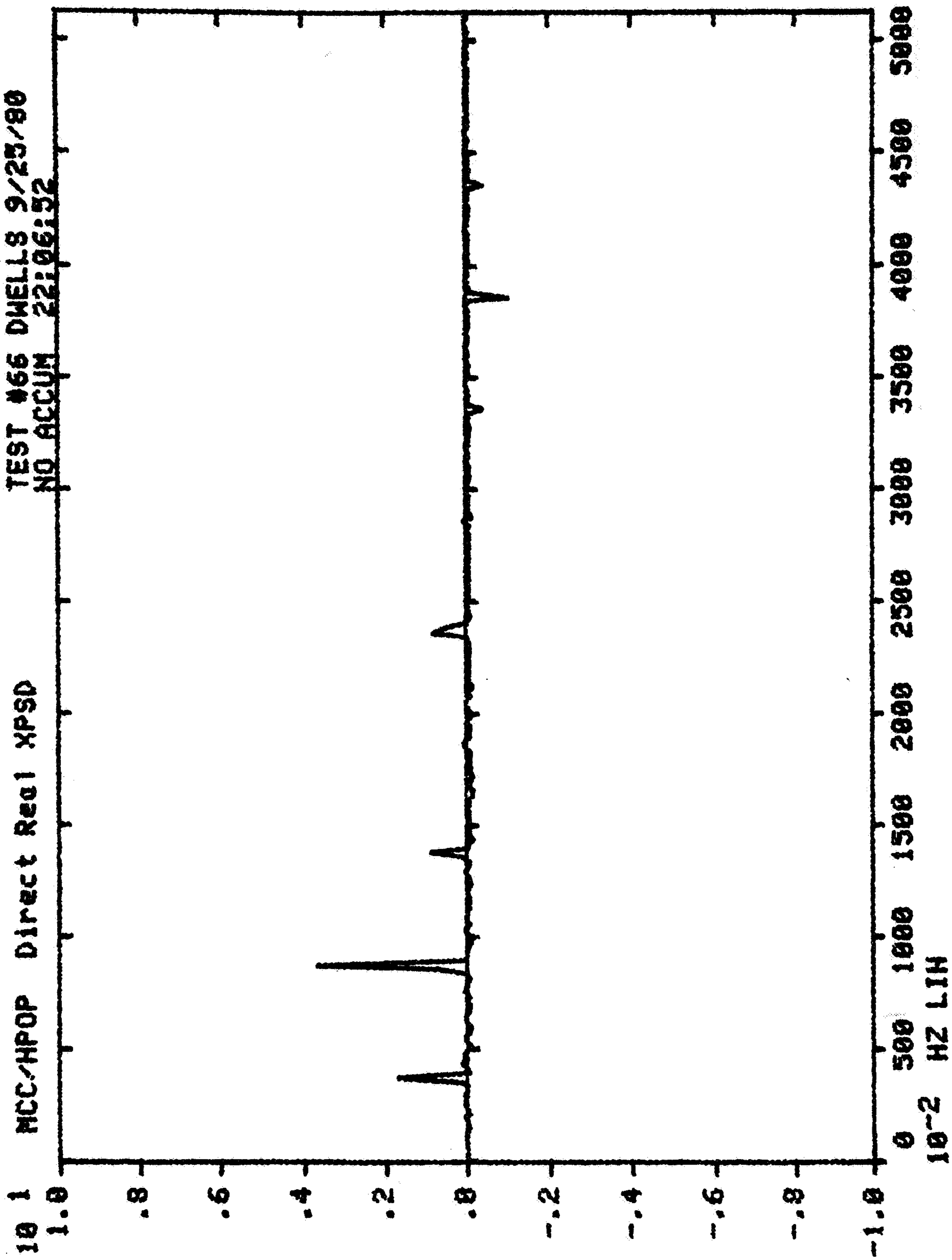
MCC/HPOP Direct H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2
HZ LIN

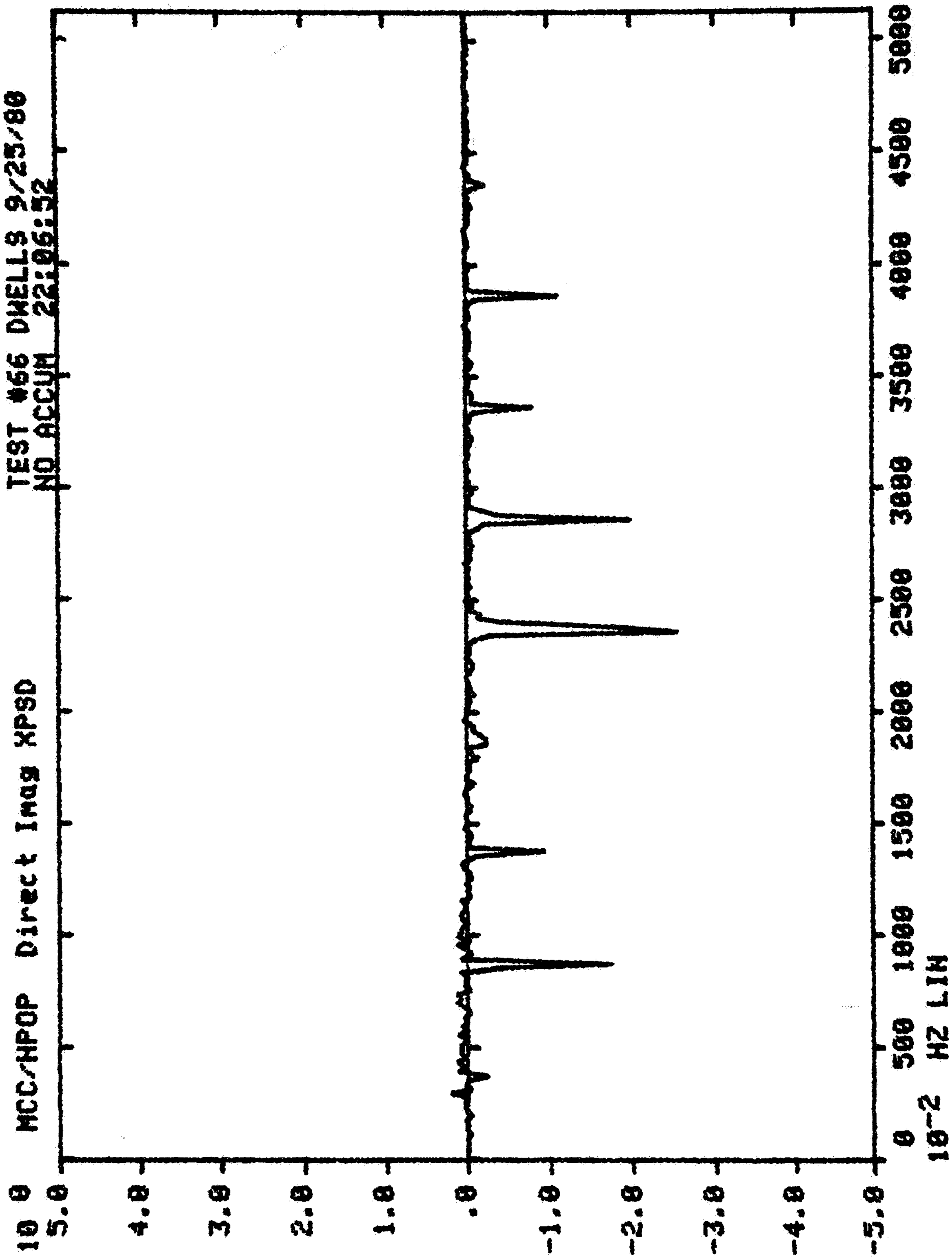

DEG MCC/HPOP Direct H(f) - Polar TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10-2 HZ LIN

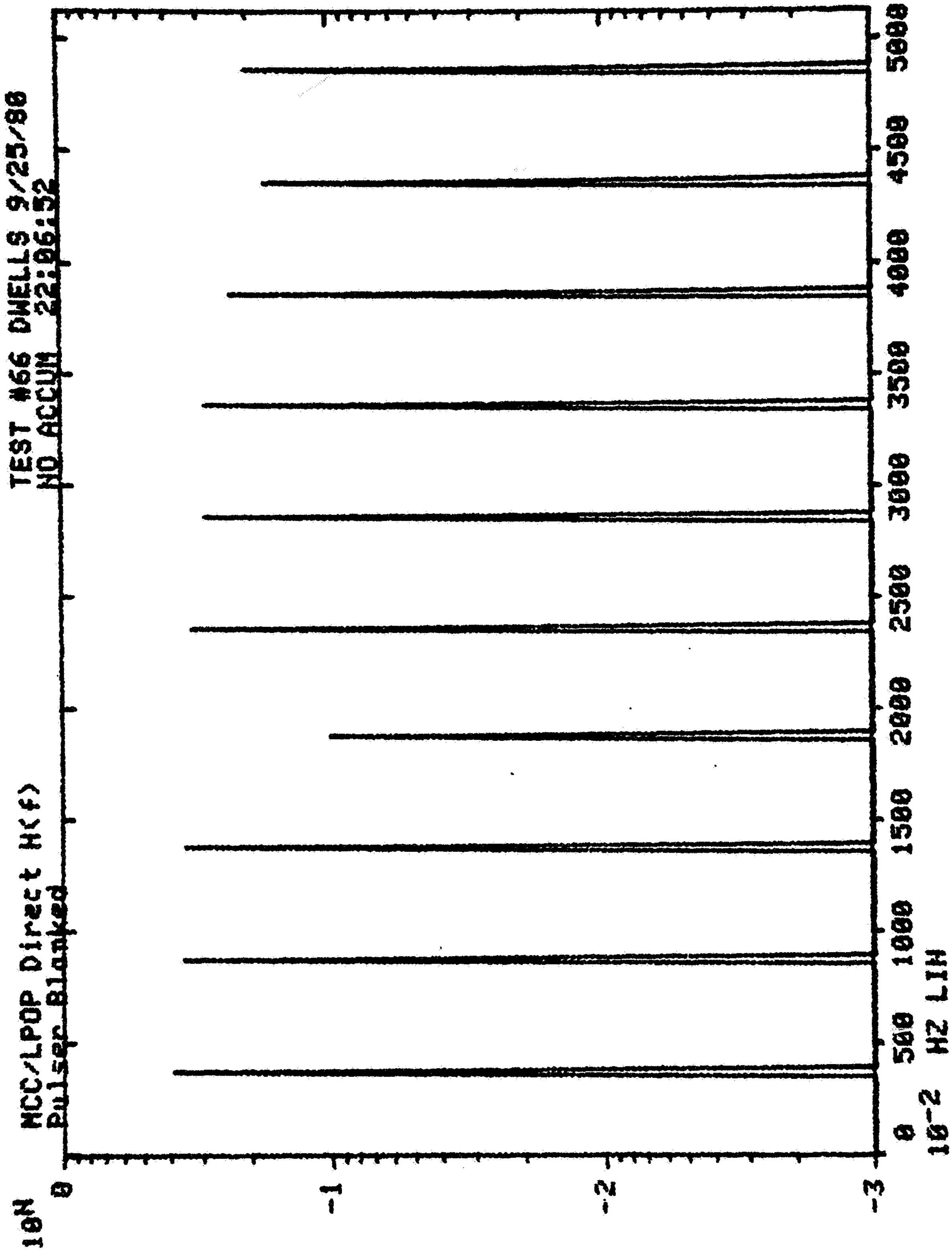


MCC/HPOP Direct Coh(f)
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10^0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

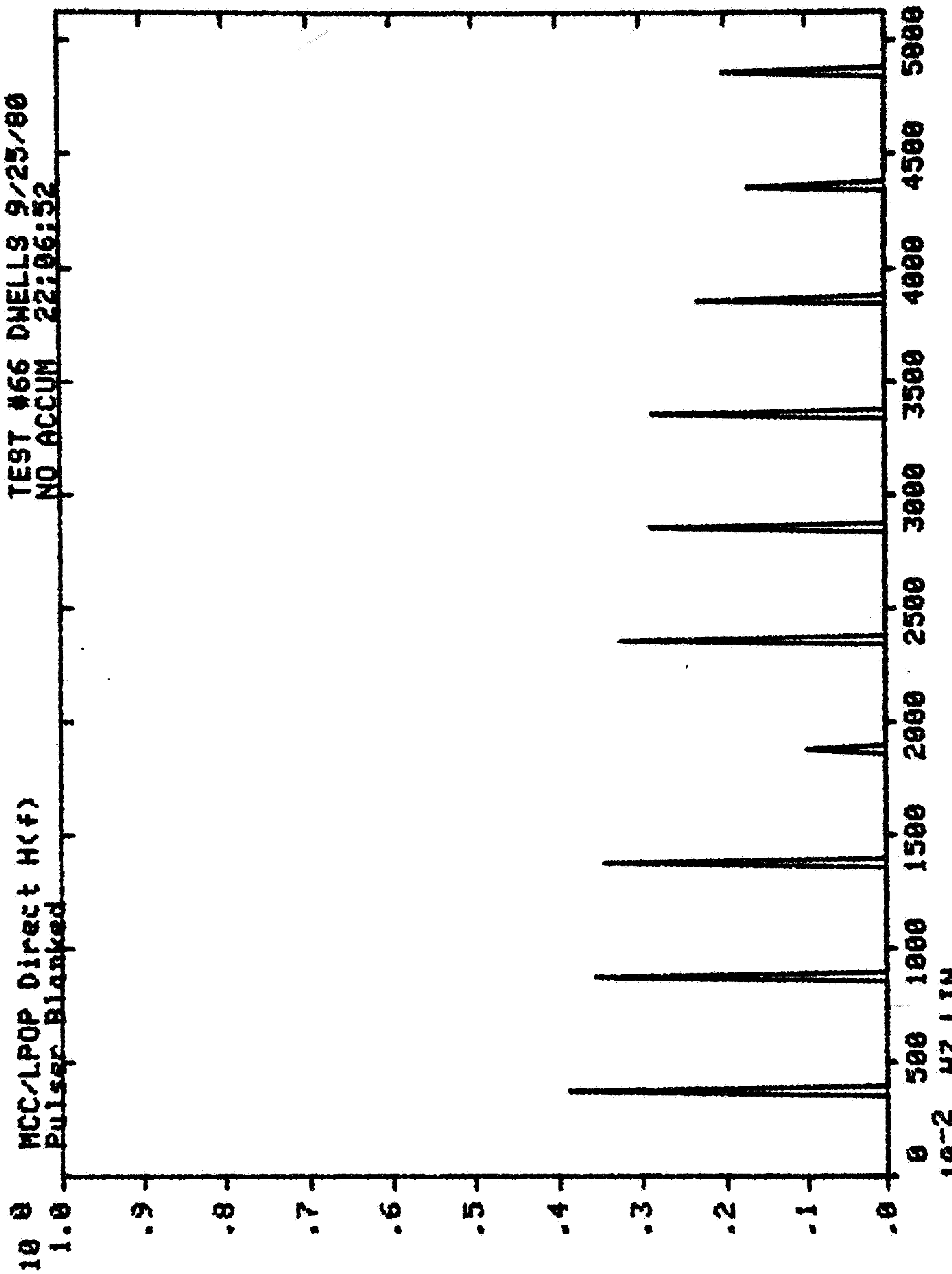
E63


MCC/HPOP Direct Real XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

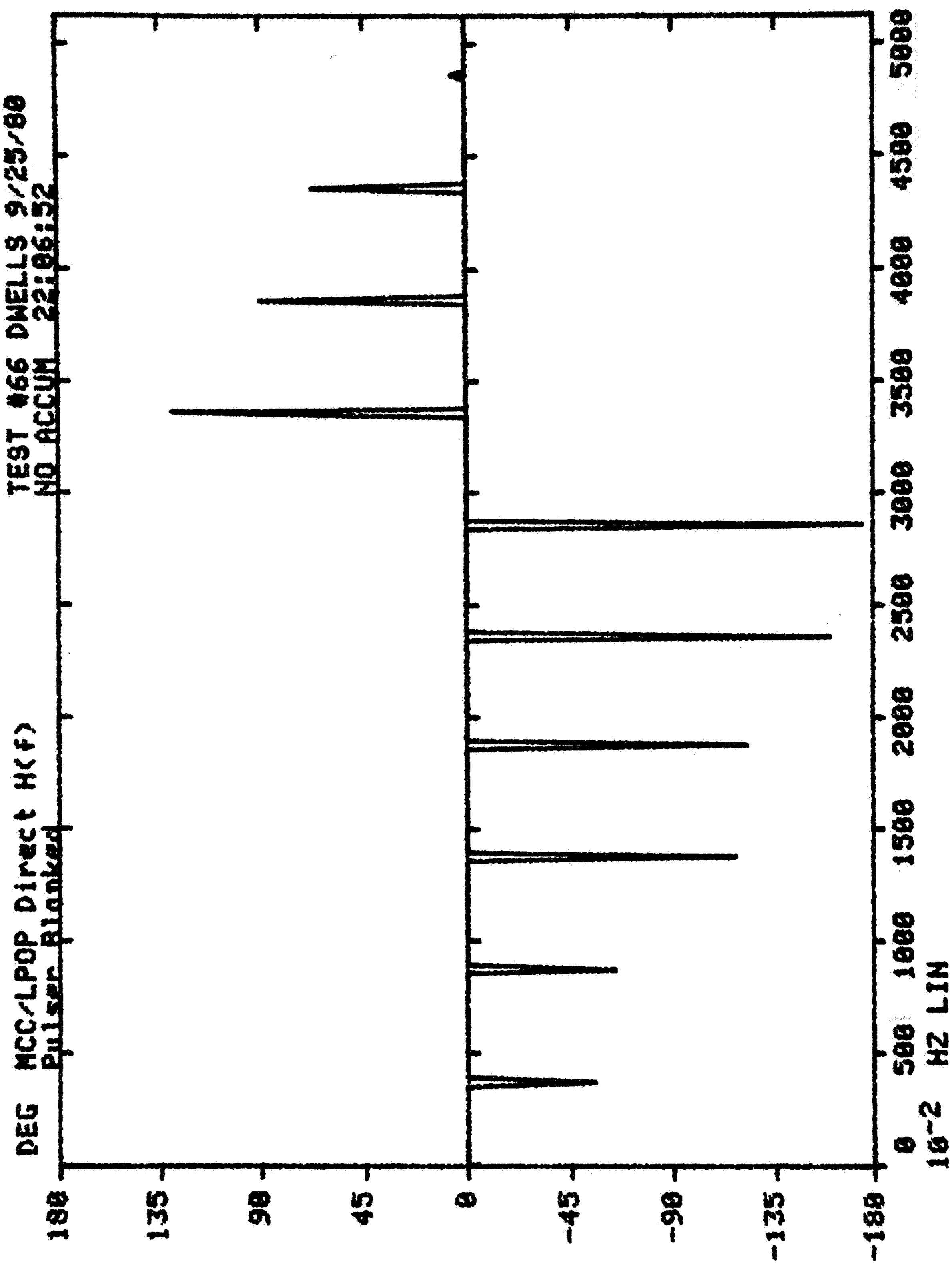

MCC/HPOP Direct Imag XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
5.0
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
-5.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
MCC/LPOP Direct H(f)
Pulser Blanked
10N
0
-1
-2
-3
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

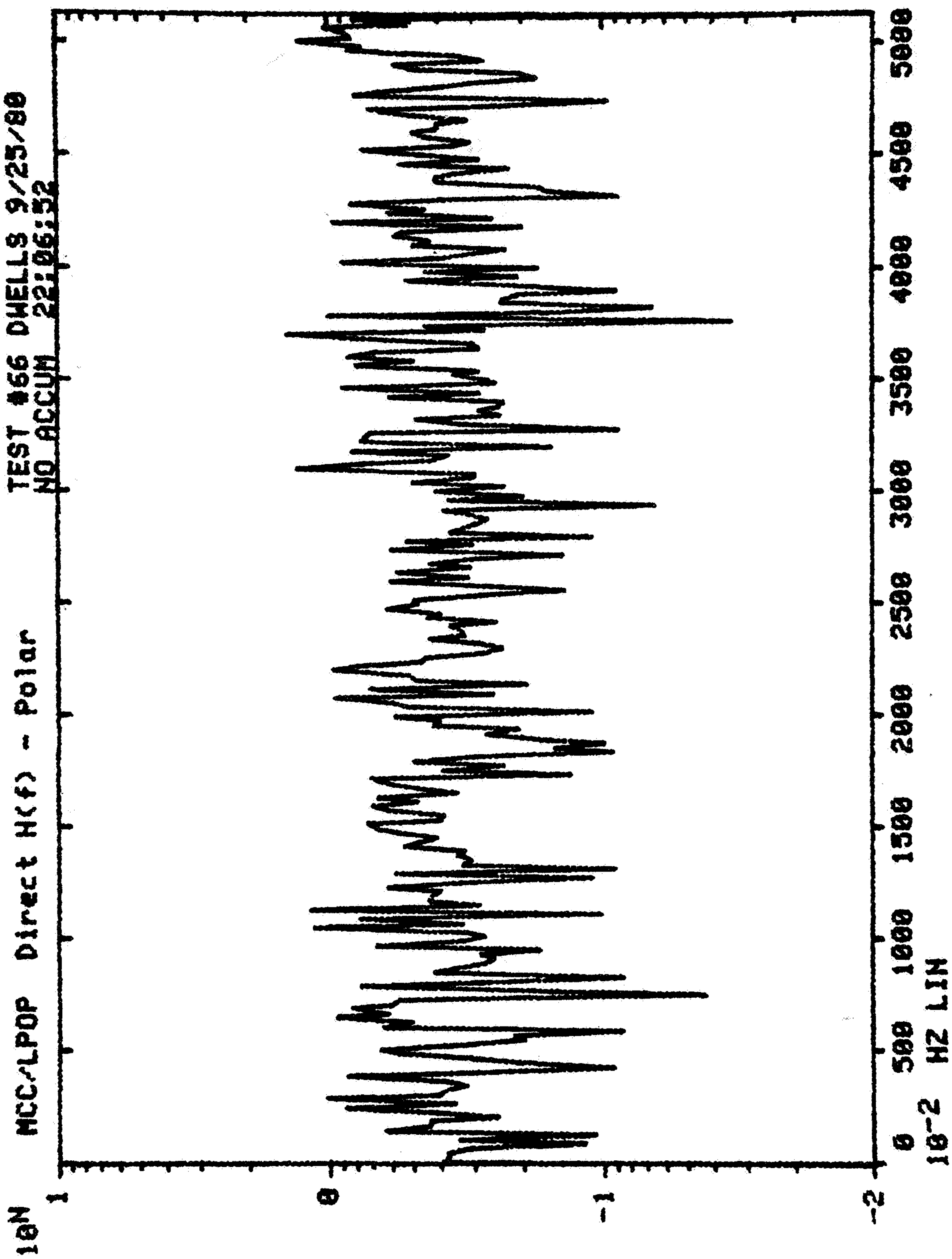
E66

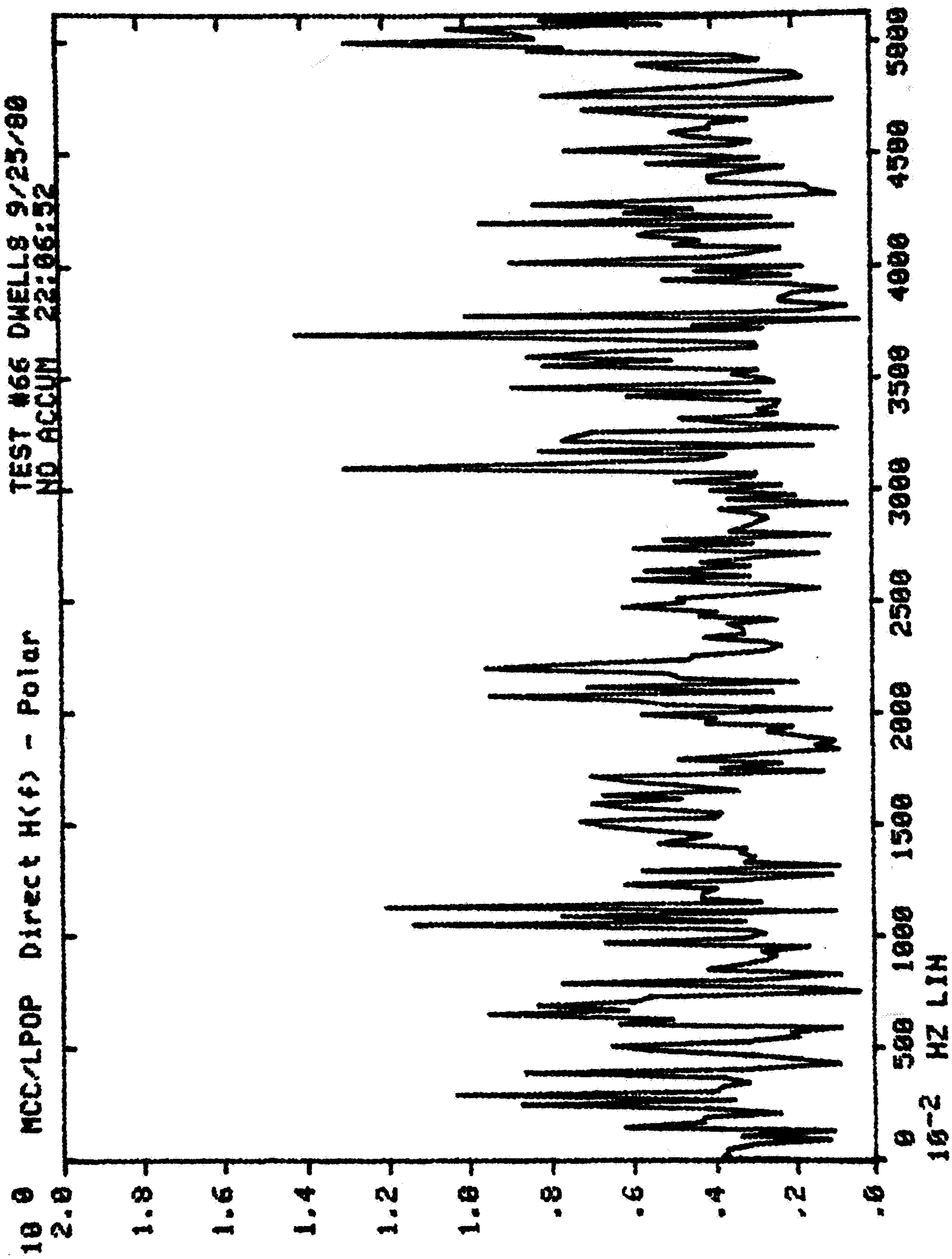


MCC/LPOP Direct H(f)
Pulsar Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
HZ LIN


DEG MCC/LPOP Direct H(f)
Pulser Blanked
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
180
135
90
45
0
-45
-90
-135
-180
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

E68


MCC/LPOP Direct H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10N
1
0
-1
-2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


MCC/LPOP Direct H(f) - Polar
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 0
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

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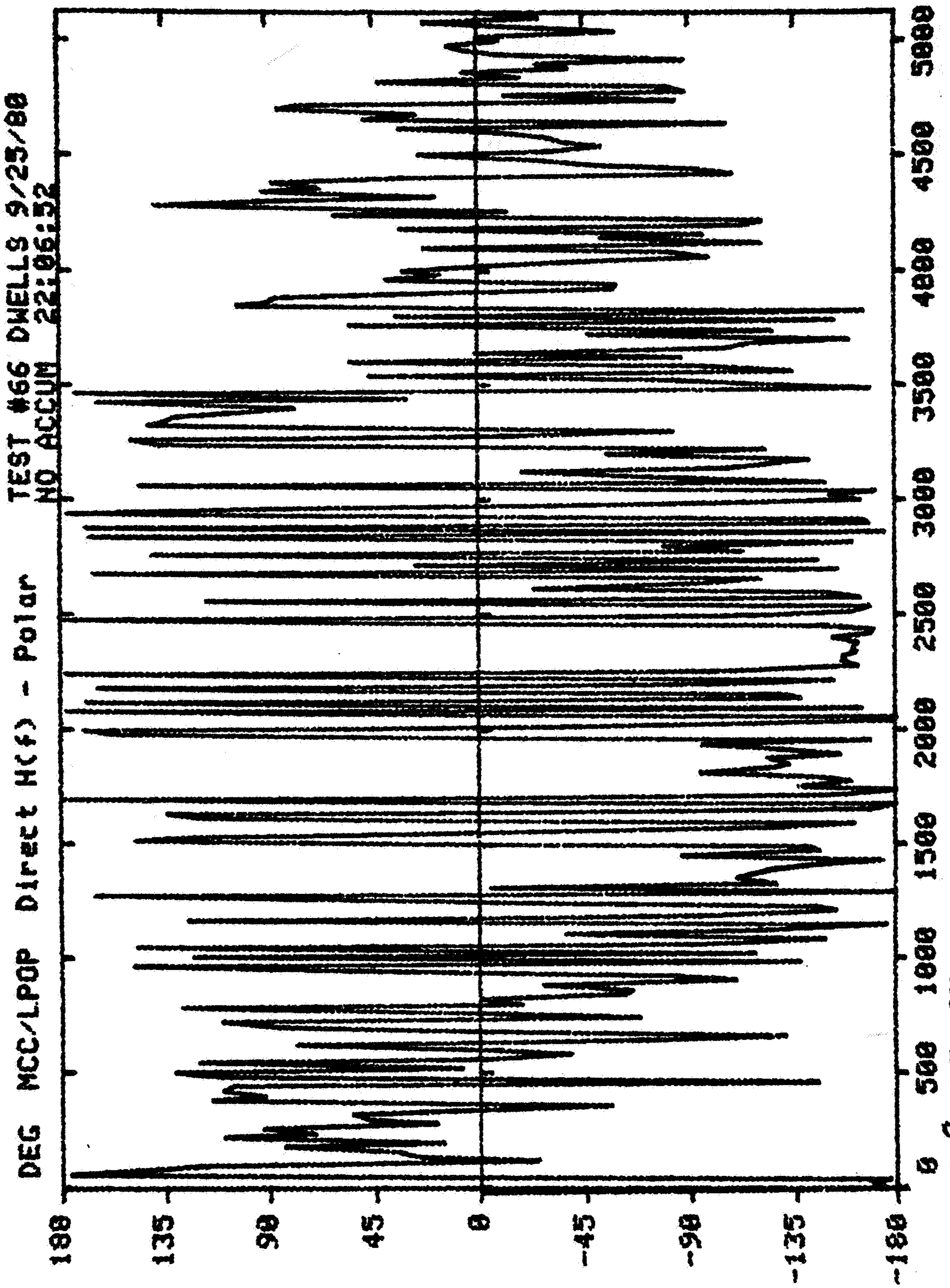
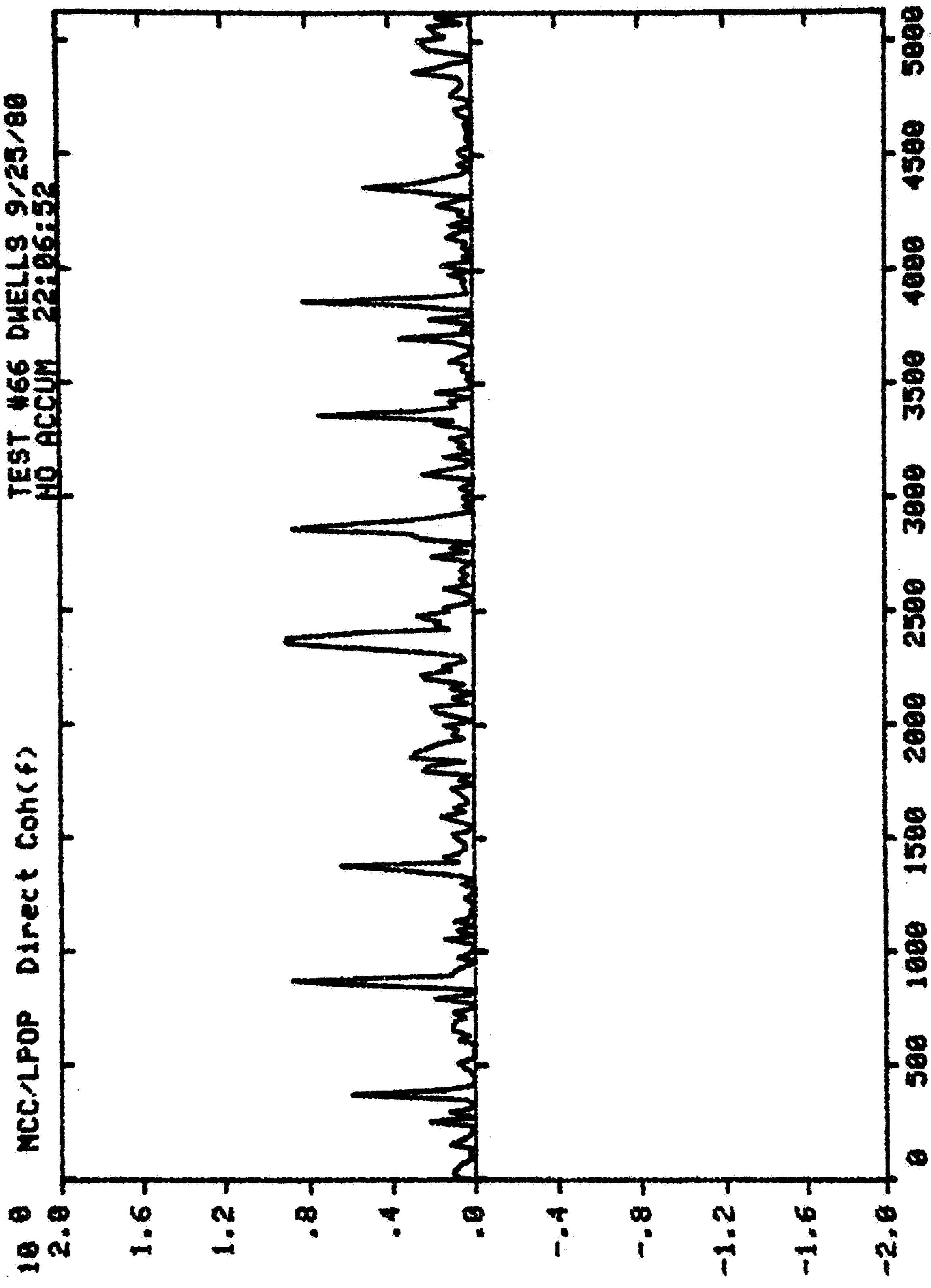
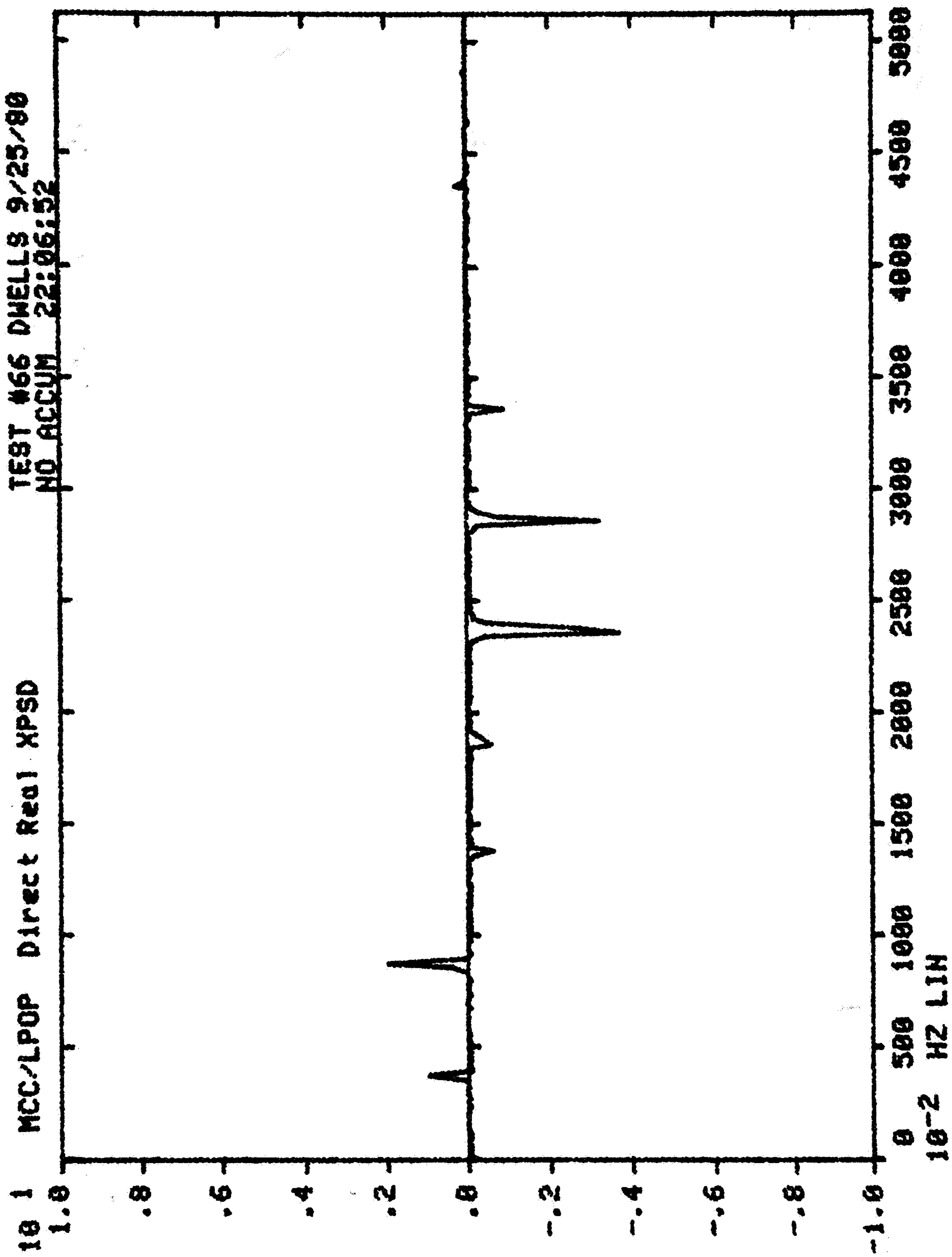


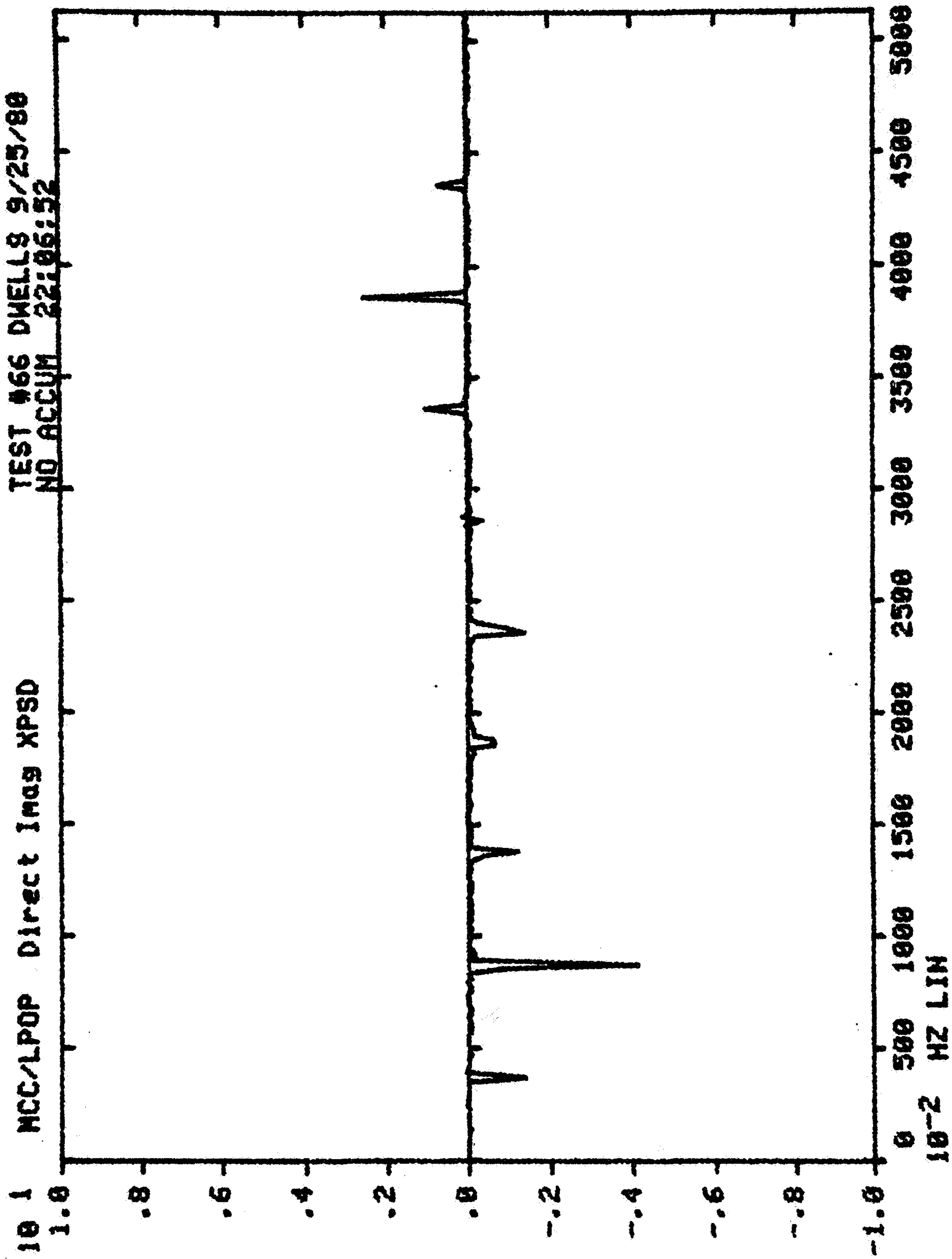

MCC/LPOP Direct Coh(f)
TEST #66 DWELLS 9/25/80
HD ACCUM 22:06:52
10 0
2.0
1.6
1.2
.8
.4
.0
-.4
-.8
-1.2
-1.6
-2.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

C-3

E72



MCC/LPOP Direct Real XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN


MCC/LPOP Direct Imag XPSD
TEST #66 DWELLS 9/25/80
NO ACCUM 22:06:52
10 1
1.0
.8
.6
.4
.2
.0
-.2
-.4
-.6
-.8
-1.0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
10^-2 HZ LIN

APPENDIX B

WYLE LABORATORIES - RESEARCH STAFF
TECHNICAL MEMORANDUM TM 84-03

ROLLING BEARING ELEMENT ROTATIONAL SPEEDS FOR THE SSME HIGH PRESSURE FUEL AND LOX TURBOPUMPS

APPENDIX B

WYLE LABORATORIES - RESEARCH STAFF
TECHNICAL MEMORANDUM TM 84-03

ROLLING BEARING ELEMENT ROTATIONAL SPEEDS FOR THE SSME HIGH PRESSURE FUEL AND LOX TURBOPUMPS

by

Wayne L. Swanson

An interim report of
work performed under contract NAS8-33508

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

FOREWORD

Wyle Laboratories' Scientific Services & Systems Group has prepared this report for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. The work was performed under contract NAS8-33508, entitled "Dynamic Analysis of SSME Vibration and Pressure Data." Technical direction and computer program coding for this study were provided by ED24 personnel of the Systems Dynamics Laboratory.

TABLE OF CONTENTS

INTRODUCTORY SUMMARY

This report consists of a series of charts, equations, and the computer program listing for determining the frequencies associated with the roller bearings of the SSME high pressure fuel turbopump (HPFTP) and high pressure oxygen turbopump (HPOTP). The frequencies are in terms of speed ratio normalized by the rotational speed of the shaft. Speed ratio was calculated for the cage, ball spin, outer race, and inner race for the different bearing parameters of the SSME HPFTP and HPOTP.

Several methods of data presentation are provided for ease in interpretation. This includes charts for the change in contact angle for both the inner and outer race, constant inner race contact angle versus outer contact angle, and charts of inner contact angle equal to outer contact angle, which is only applicable for the case of slow rotational speed and/or applied radial load of large magnitude.

The data from two static firing tests are also included where the cage and outer race frequencies were noted on internal strain gages mounted directly on the bearing holder. Several attempts were made using different analysis techniques (including adaptive filtering, cross PSDs, etc.) to isolate these frequencies in the external accelerometer data. To date these efforts have not been successful.

TECHNICAL DISCUSSION

The speed ratio for the cage, ball spin, and outer and inner race are defined as follows:[1]

$$\text{Cage Speed Ratio} = \frac{1 - \gamma' \cos \alpha_i}{1 + \cos (\alpha_i - \alpha_o)}$$

$$\text{Outer Race Speed Ratio} = \frac{N_b \, (1 - \gamma' \cos \alpha_i)}{1 + \cos (\alpha_i - \alpha_o)}$$

$$\text{Inner Race Speed Ratio} = \frac{N_b \, \cos (\alpha_i - \alpha_o) + \gamma' \cos \alpha_i}{1 + \cos (\alpha_i - \alpha_o)}$$

$$\text{Ball Spin Ratio} = \left\{ \left[(\cos \alpha_o + \tan \beta \sin \alpha_o)(1 + \gamma' \cos \alpha_o)^{-1} + (\cos \alpha_i + \tan \beta \sin \alpha_i)(1 - \gamma' \cos \alpha_i)^{-1} \right] \gamma' \cos \beta \right\}^{-1}$$

where $\tan \beta = \dfrac{\sin \alpha_o}{\cos \alpha_o + \gamma'}$

and

α_o = outer raceway contact angle

α_i = inner raceway contact angle

γ' = D/d_m

D = ball diameter

d_m = pitch diameter

N_b = number of balls

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[1]Tedric A. Harris. Rolling Bearing Analysis, John Wiley & Sons, New York, 1966.

The bearing parameters used for this study are as follows:

High Pressure Fuel Turbopump (HPFTP)

Pump and turbine bearings:

Ball diameter = 0.343750 inch

Pitch diameter = 2.34 inches

Number of balls = 14

Thrust bearings:

Ball diameter = 0.656250 inch

Pitch diameter = 3.84 inches

Number of balls = 13

High Pressure Oxygen Turbopump (HPOTP)

Turbine end bearings:

Ball diameter = 0.50 inch

Pitch diameters = 3.196, 3.17, 3.20, and 3.19 inches

Number of balls = 13

Pump end bearings:

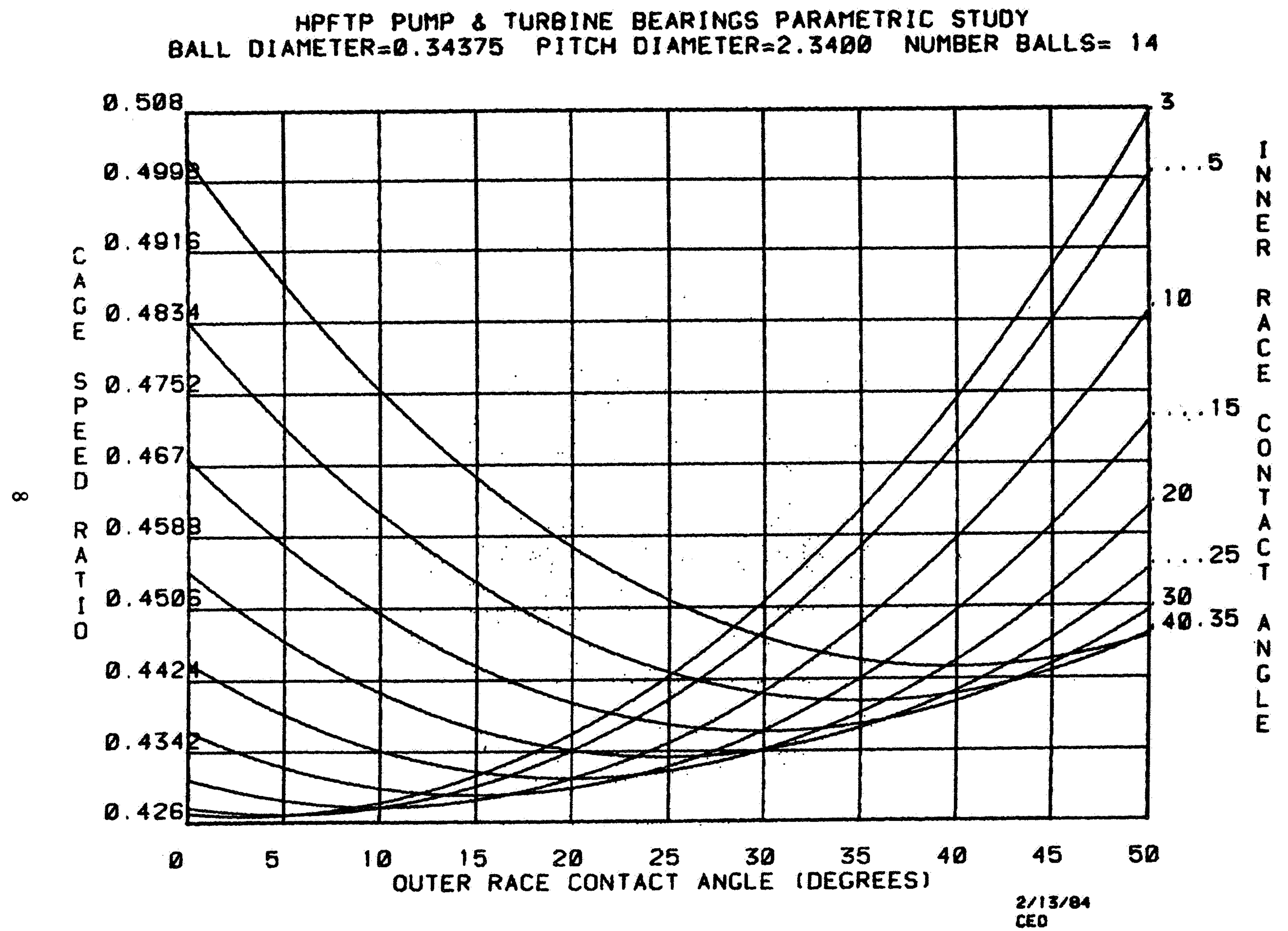
Ball diameter = 0.4375 inch

Pitch diameter = 2.56 inches

Number of balls = 13

SPEED RATIO OF
HPFTP PUMP AND TURBINE BEARINGS

Ball Diameter	= 0.343750 inch
Pitch Diameter	= 2.34 inches
Number of Balls	= 14


HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
CAGE SPEED RATIO
0.508
0.4998
0.4916
0.4834
0.4752
0.467
0.4588
0.4506
0.4424
0.4342
0.426
0 5 10 15 20 25 30 35 40 45 50
OUTER RACE CONTACT ANGLE (DEGREES)
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
40 35
2/13/84
CEO

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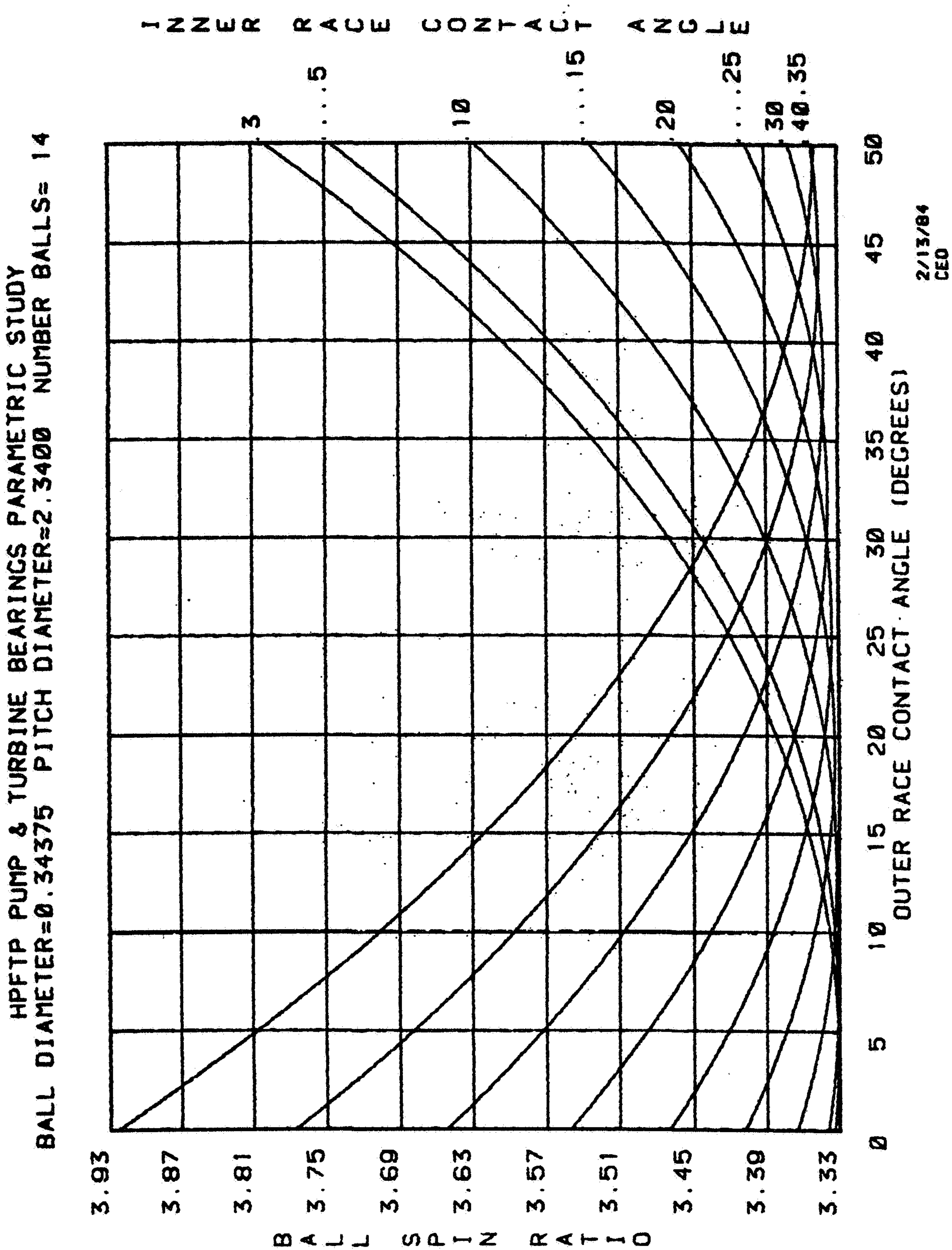
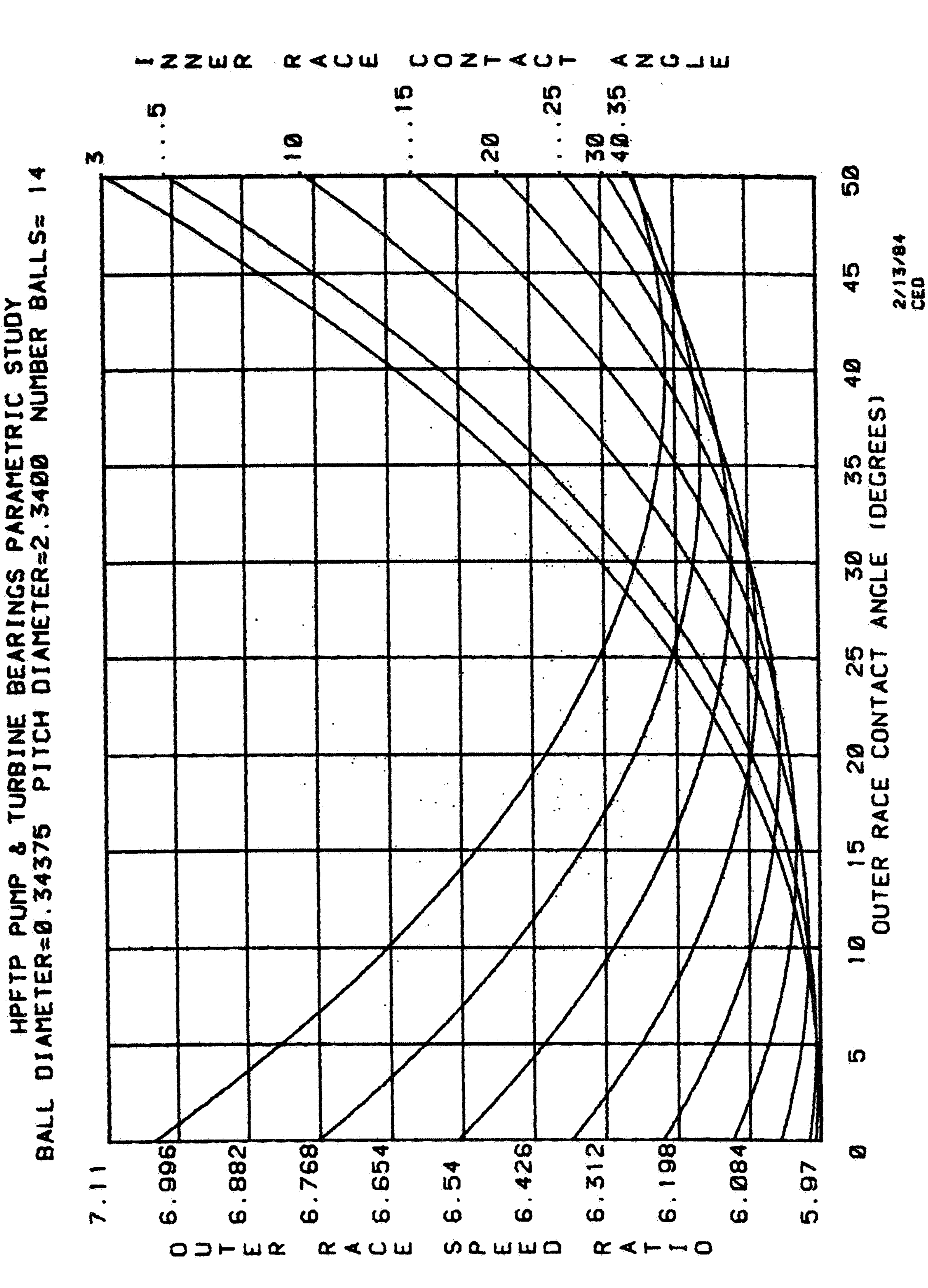
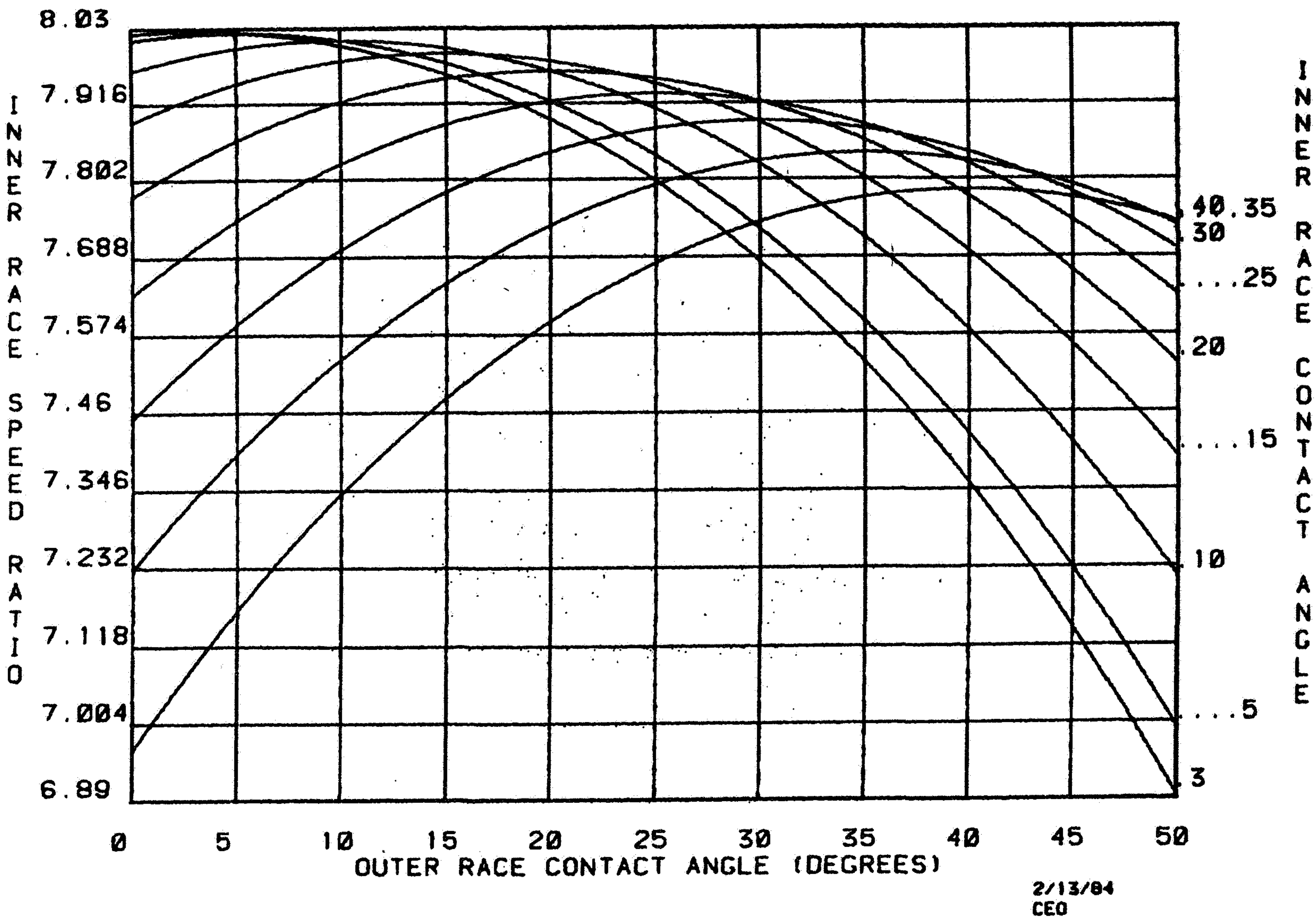
OF POOR QUALITY




HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
35
40
OUTER RACE SPEED RATIO
7.11
6.996
6.882
6.768
6.654
6.54
6.426
6.312
6.198
6.084
5.97
OUTER RACE CONTACT ANGLE (DEGREES)
0
5
10
15
20
25
30
35
40
45
50
2/13/84
CED

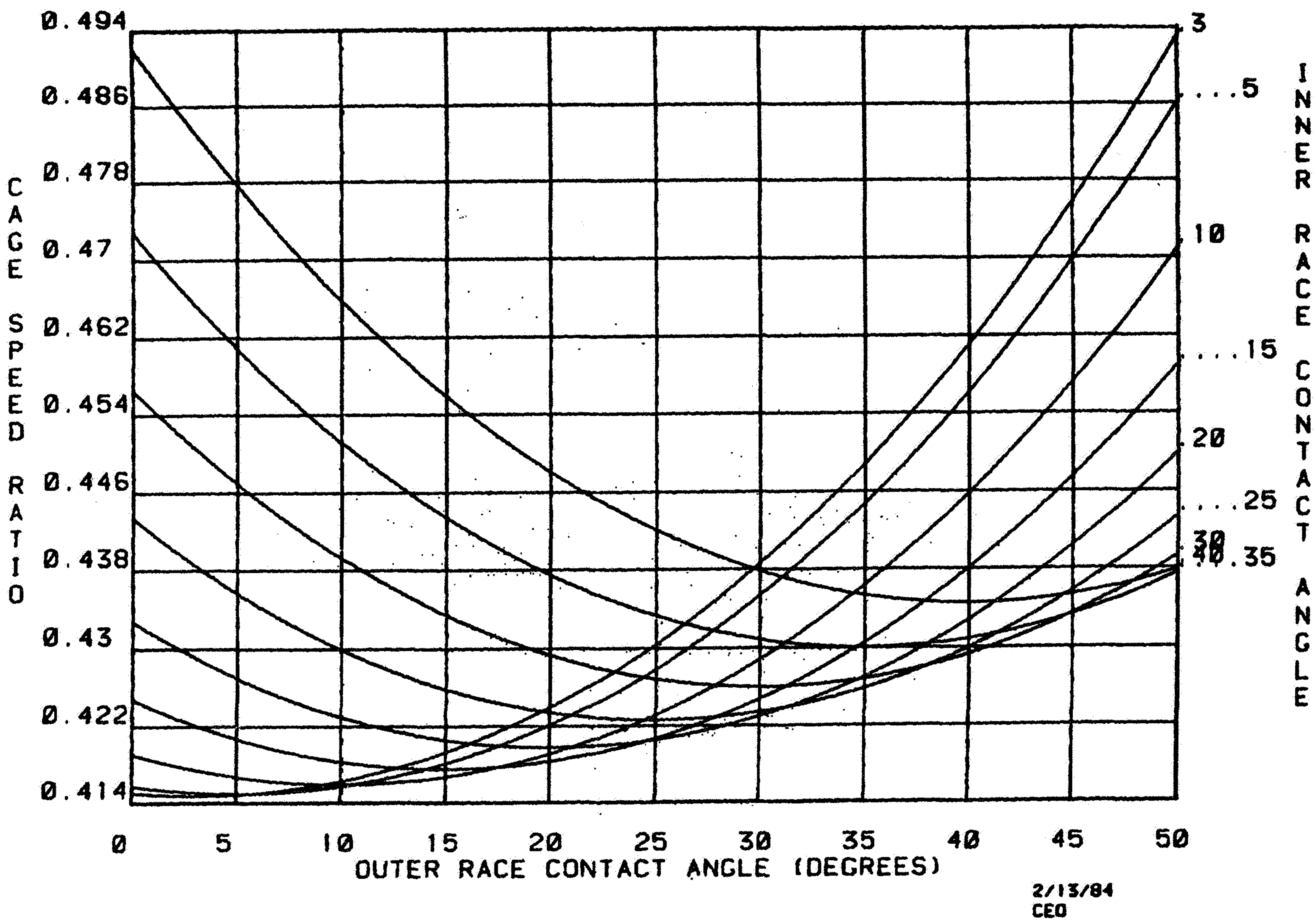
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14

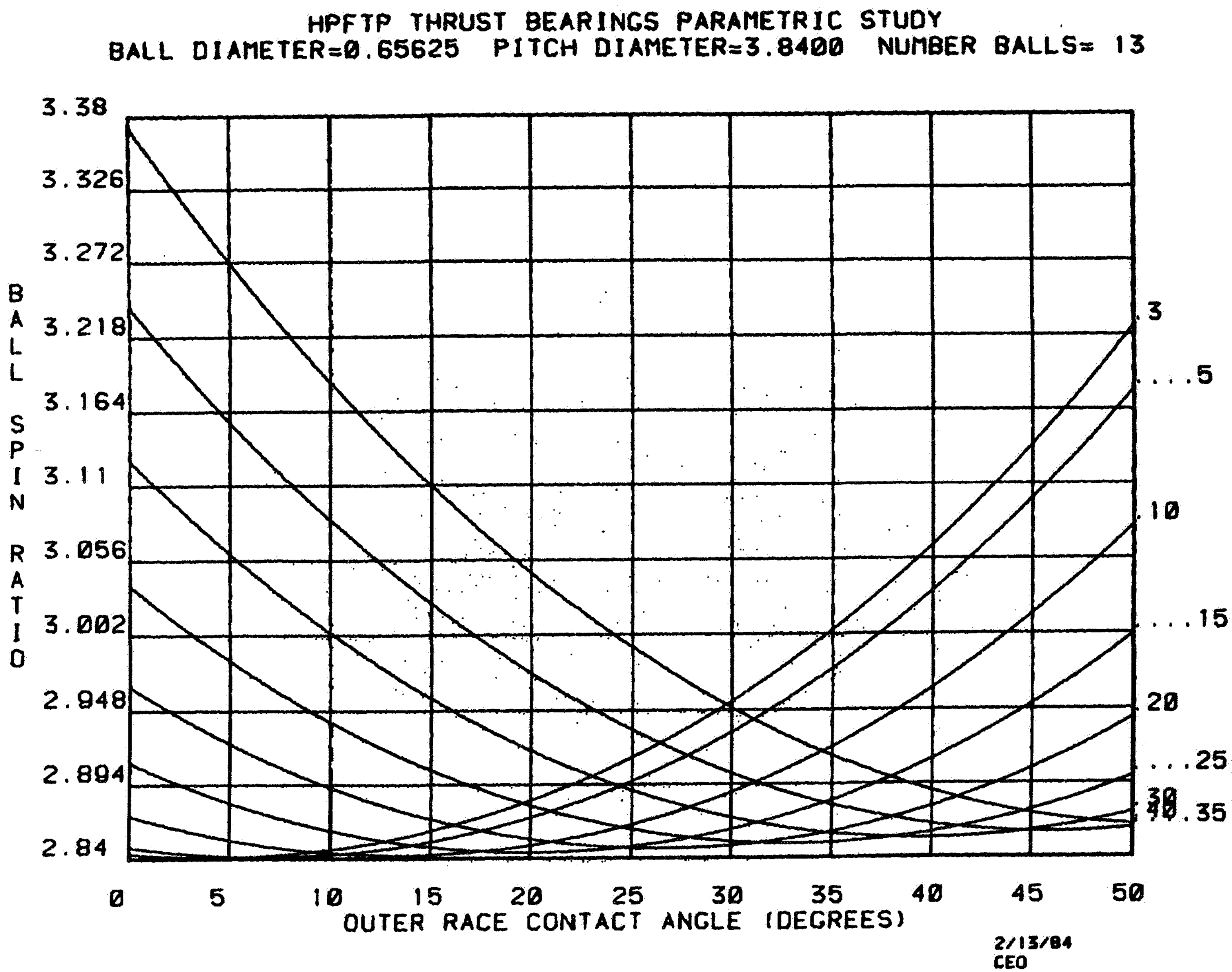


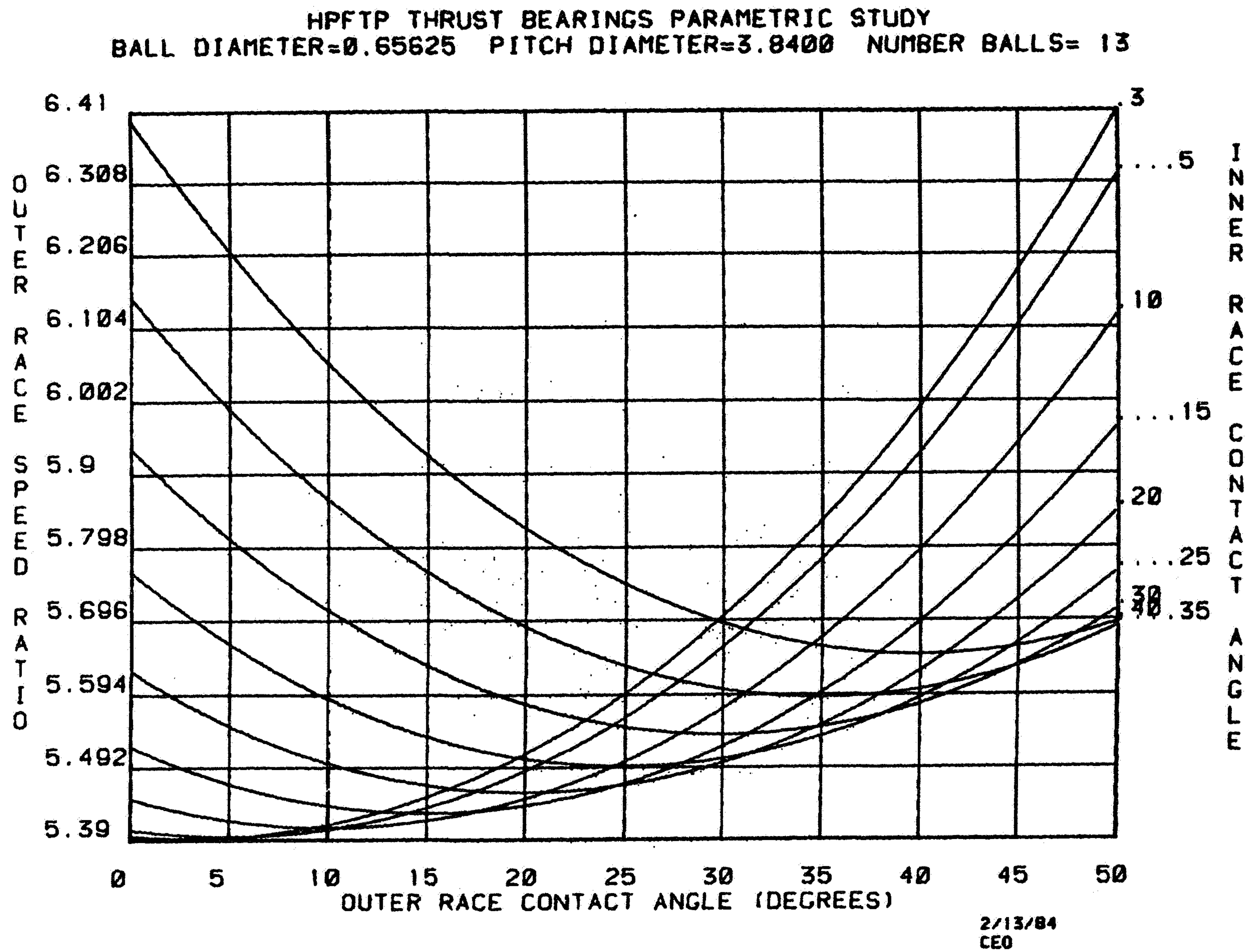
SPEED RATIO OF HPFTP THRUST BEARINGS

Ball Diameter	=	0.656250 inch
Pitch Diameter	=	3.84 inches
Number of Balls	=	13

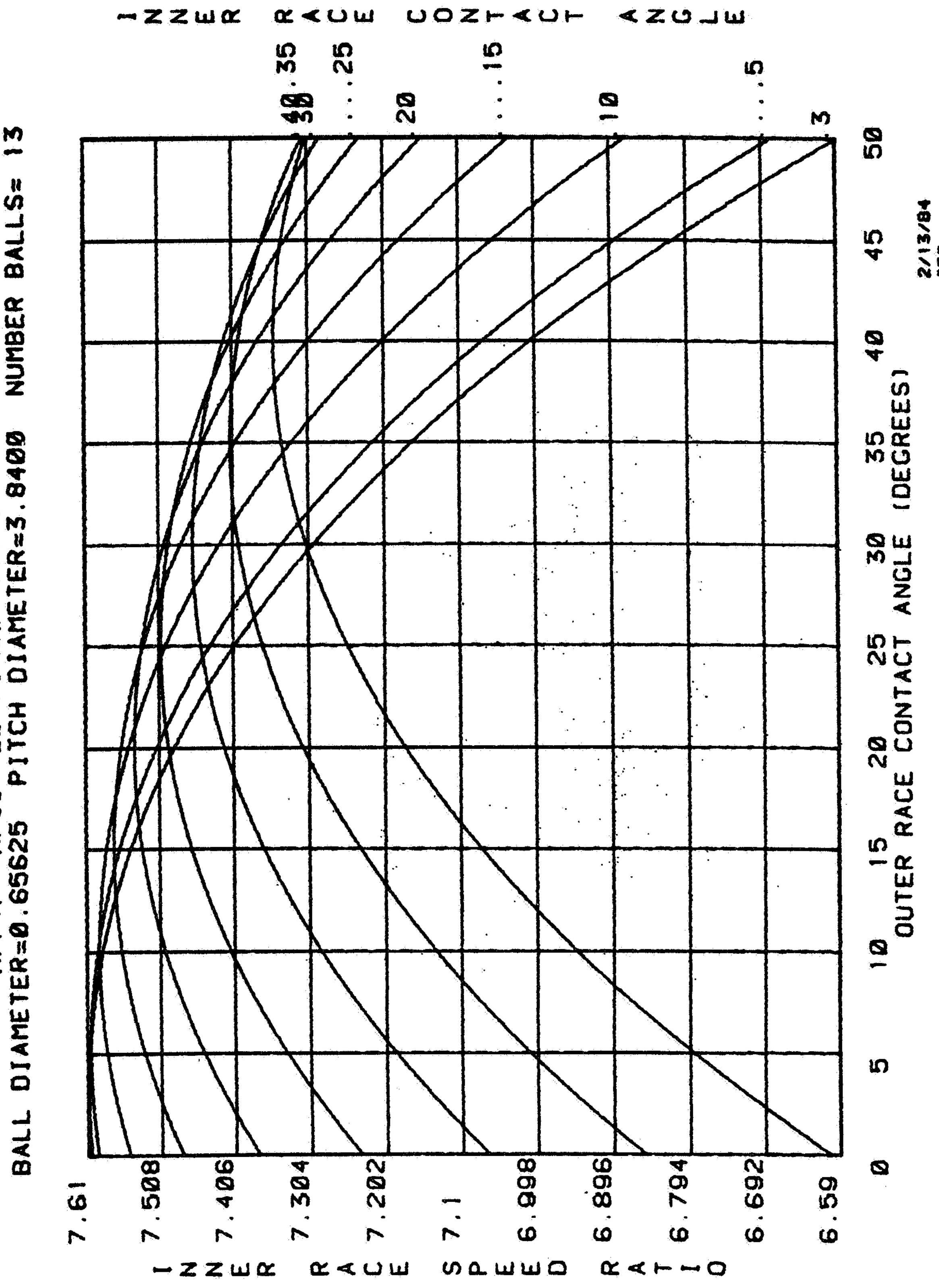
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13




HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
BALL SPIN RATIO
3.38
3.326
3.272
3.218
3.164
3.11
3.056
3.002
2.948
2.894
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
35
40
2/13/84
CEO



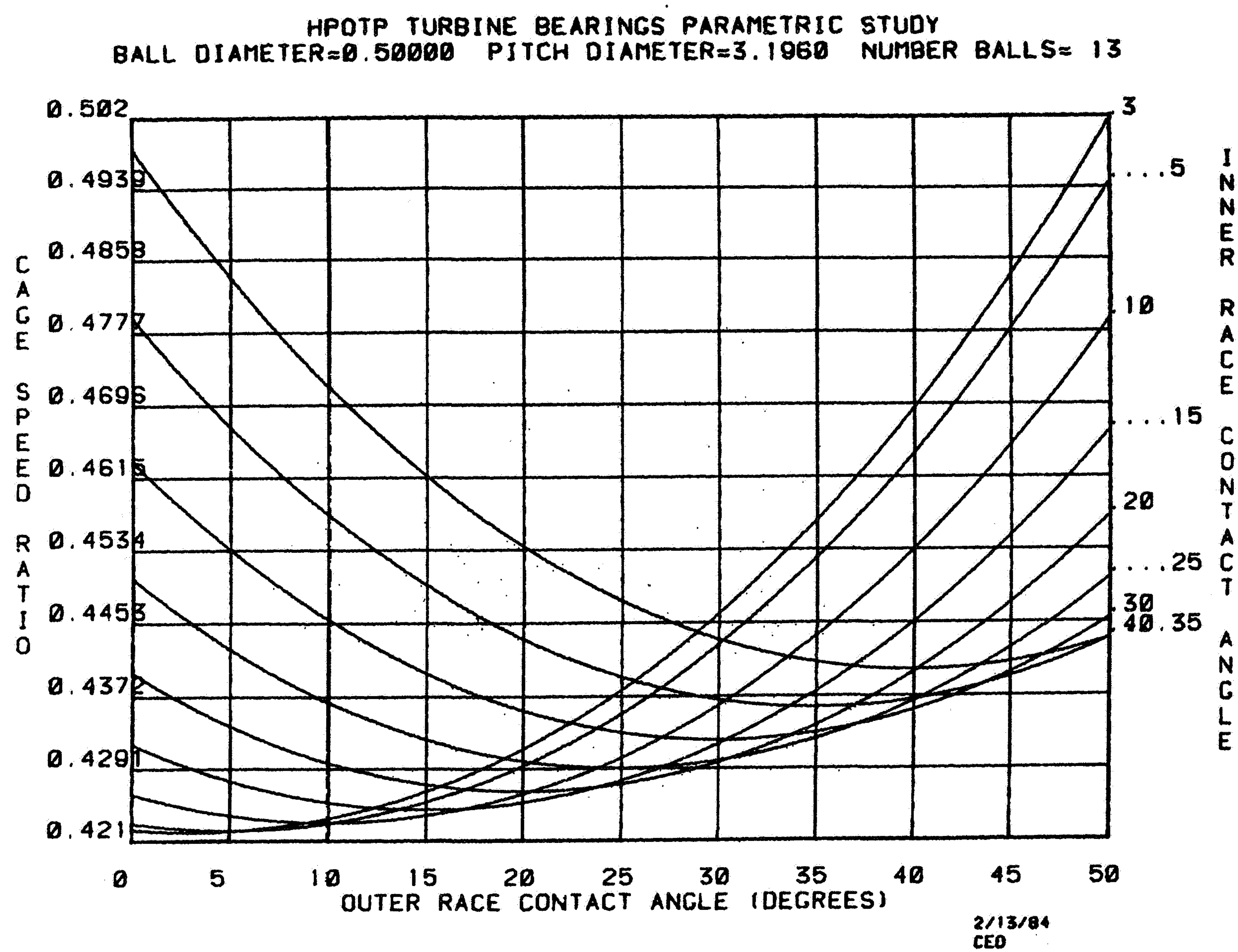
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
OUTER RACE SPEED RATIO
6.41
6.308
6.206
6.104
6.002
5.9
5.798
5.696
5.594
5.492
5.39
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
INNER RACE CONTACT ANGLE
.3
...5
.10
...15
.20
...25
.30
.40
.35
2/13/84
CEO



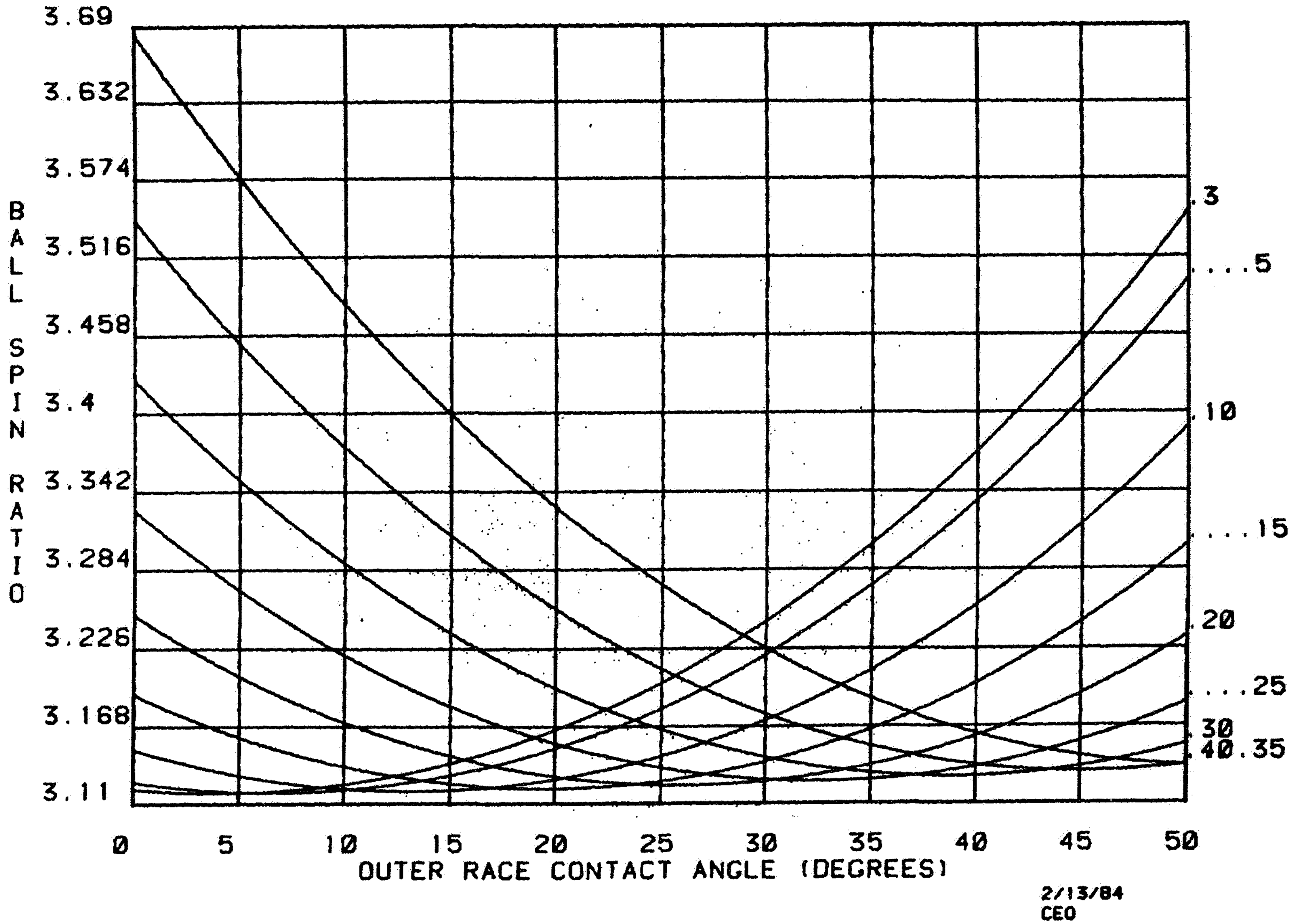
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE
40 .35
30
.25
20
.15
10
.5
3
INNER RACE SPEED RATIO
7.61
7.508
7.406
7.304
7.202
7.1
6.998
6.896
6.794
6.692
6.59
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

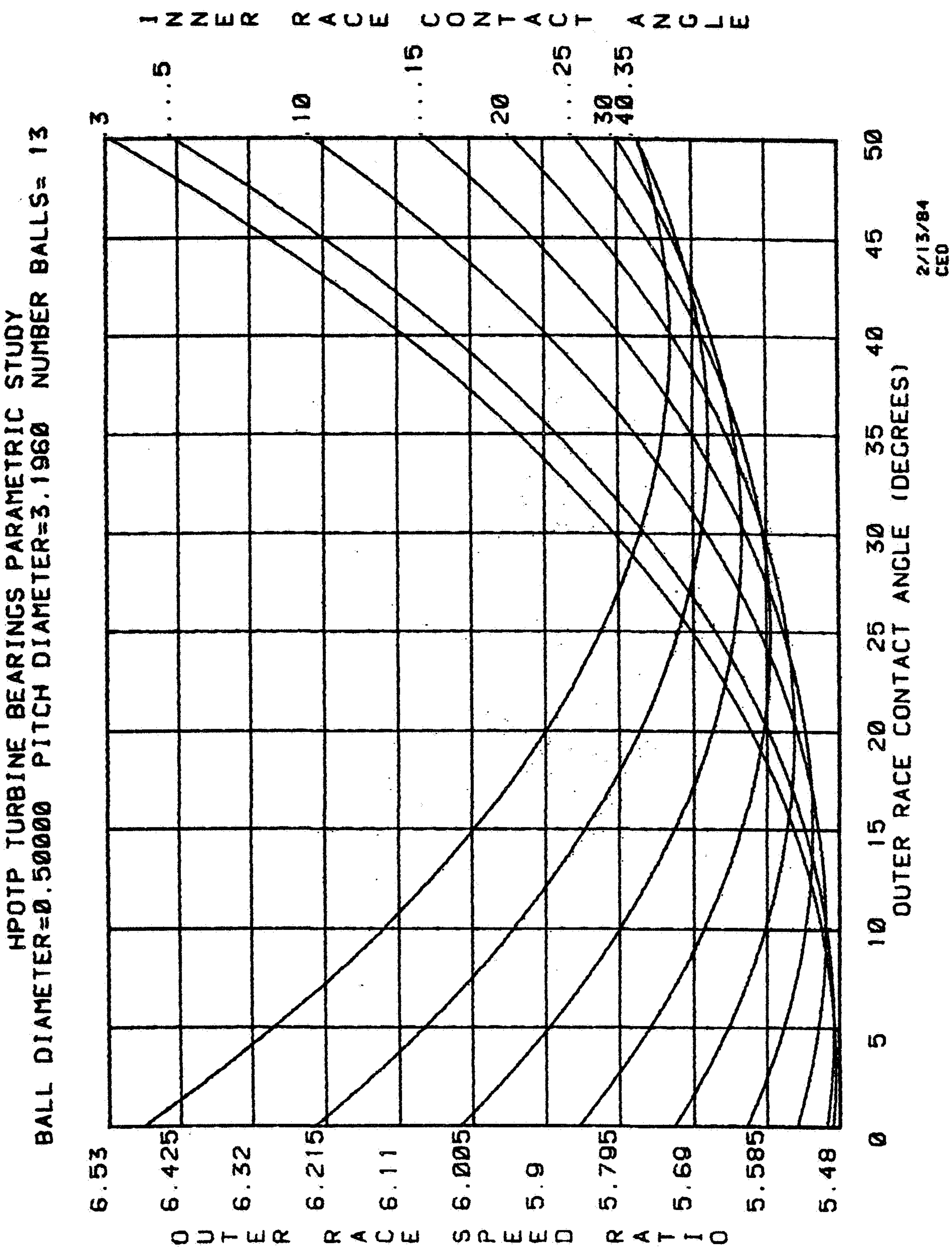
SPEED RATIO OF
HPOTP TURBINE BEARINGS

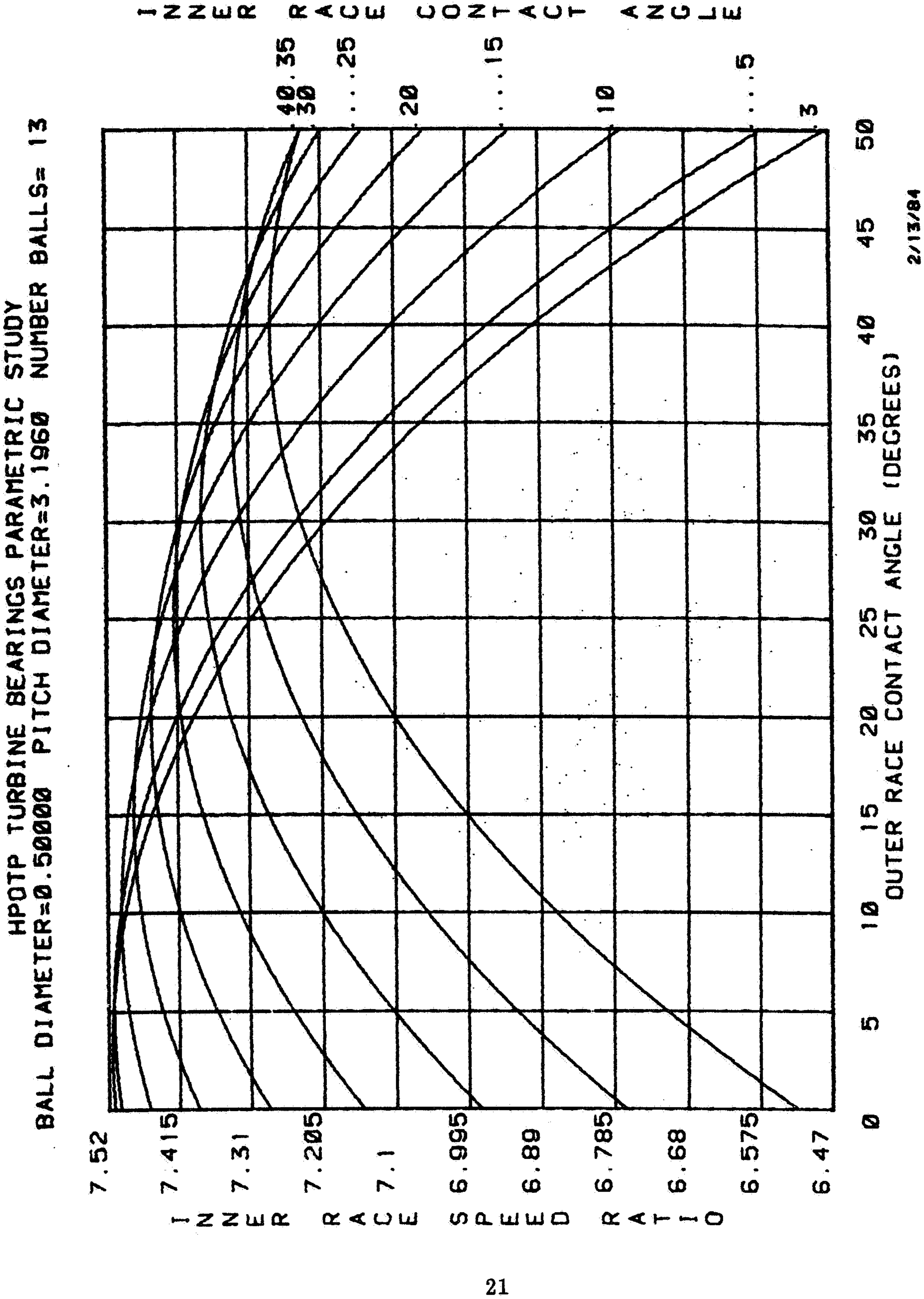
Ball Diameter	=	0.50 inch
Pitch Diameter	=	3.196 inches
Number of Balls	=	13


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
CAGE SPEED RATIO
0.502
0.4939
0.4858
0.4777
0.4696
0.4615
0.4534
0.4453
0.4372
0.4291
0.421
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
40
35
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13



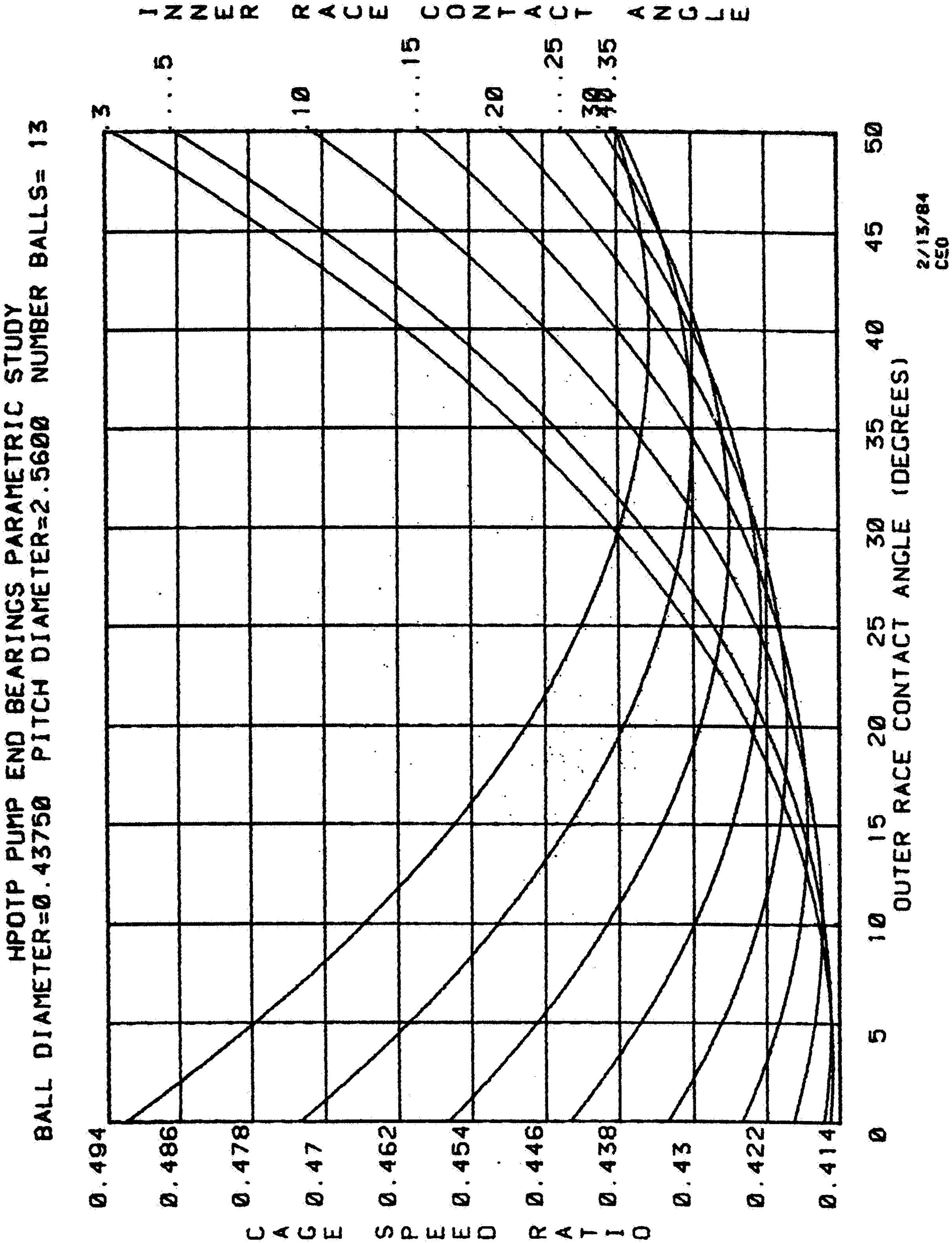

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.19600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
35
40
OUTER RACE SPEED RATIO
6.53
6.425
6.32
6.215
6.11
6.005
5.9
5.795
5.69
5.585
5.48
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO



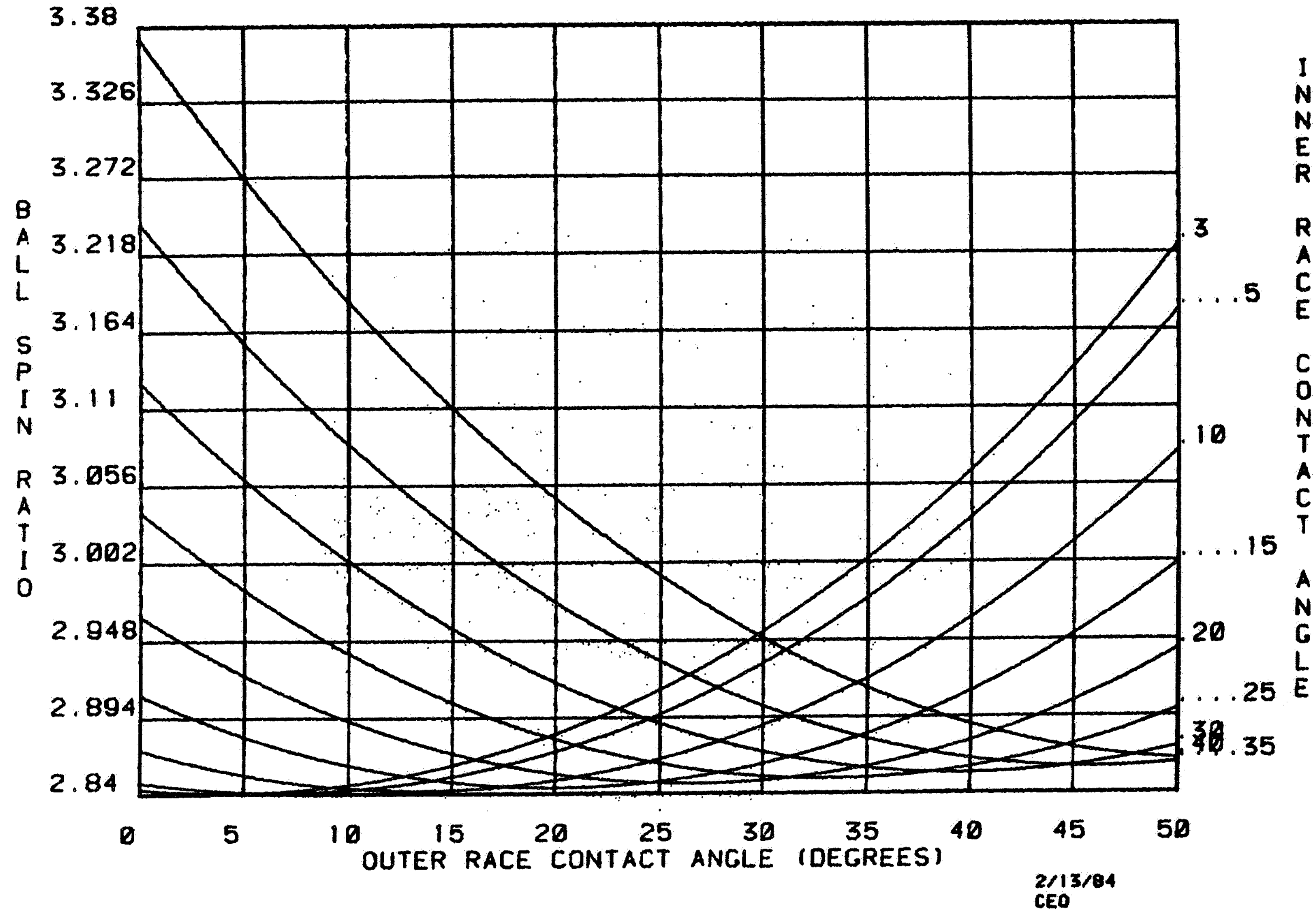
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.19600 NUMBER BALLS= 13
INNER RACE SPEED RATIO
7.52
7.415
7.31
7.205
7.1
6.995
6.89
6.785
6.68
6.575
6.47
OUTER RACE CONTACT ANGLE (DEGREES)
0
5
10
15
20
25
30
35
40
45
50
INNER RACE CONTACT ANGLE
40
35
30
25
20
15
10
5
3
2/13/84
CEO

SPEED RATIO OF
HPOTP PUMP END BEARINGS

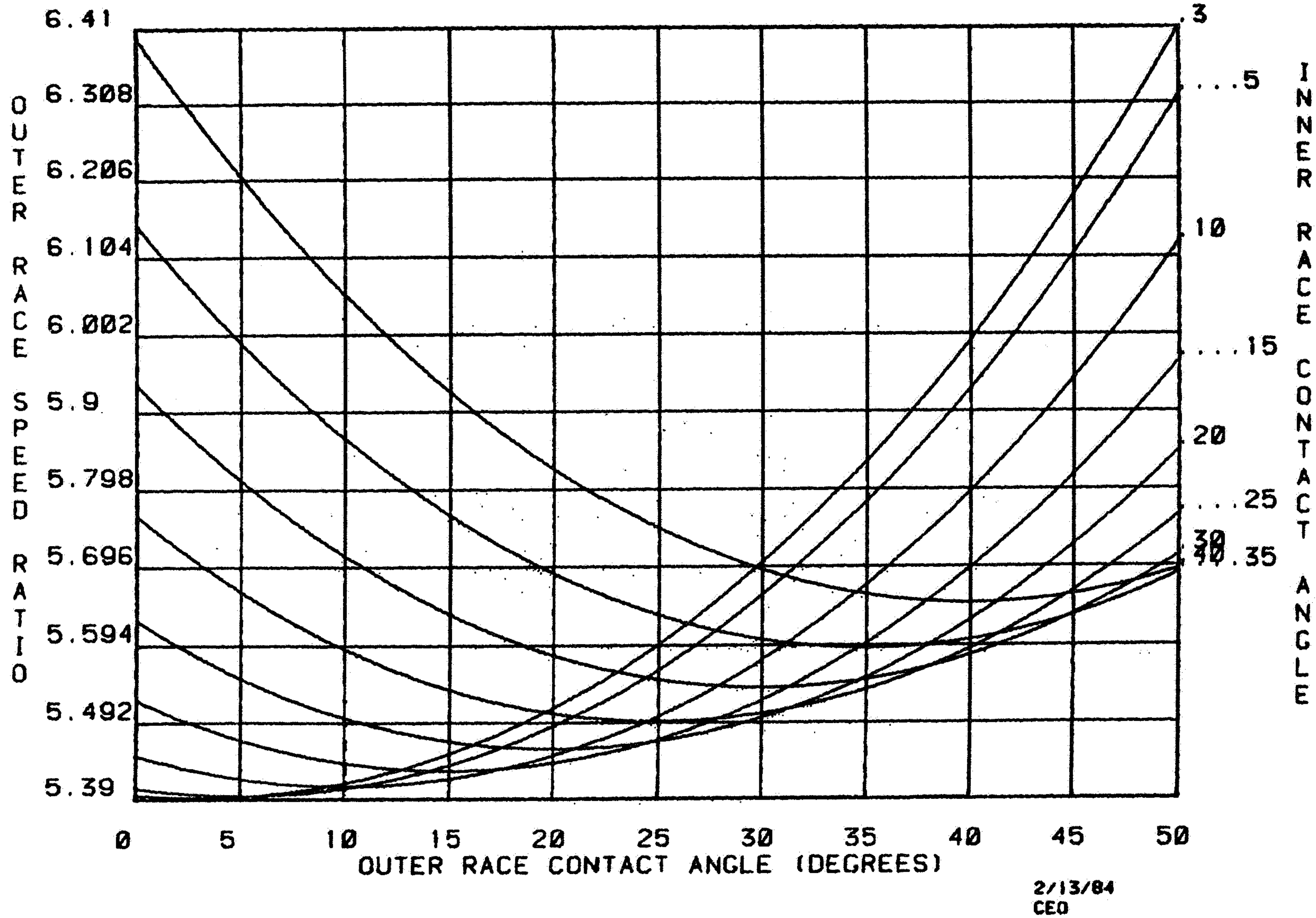
Ball Diameter = 0.4375 inch
Pitch Diameter = 2.56 inches
Number of Balls = 13

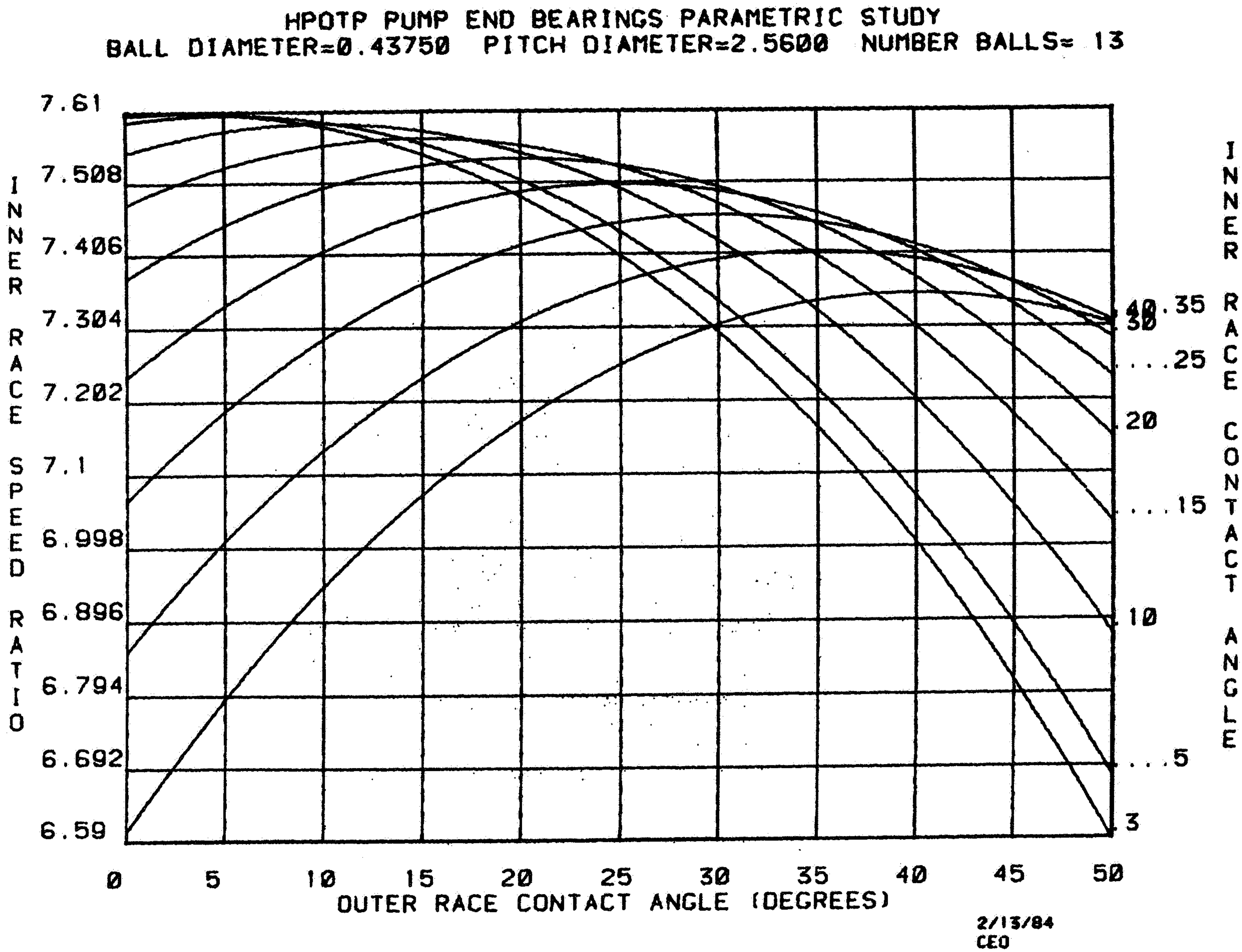

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE
3
5
10
15
20
25
30
35
40
0.494
0.486
0.478
0.47
0.462
0.454
0.446
0.438
0.43
0.422
0.414
CAGE SPEED RATIO
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13



HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13

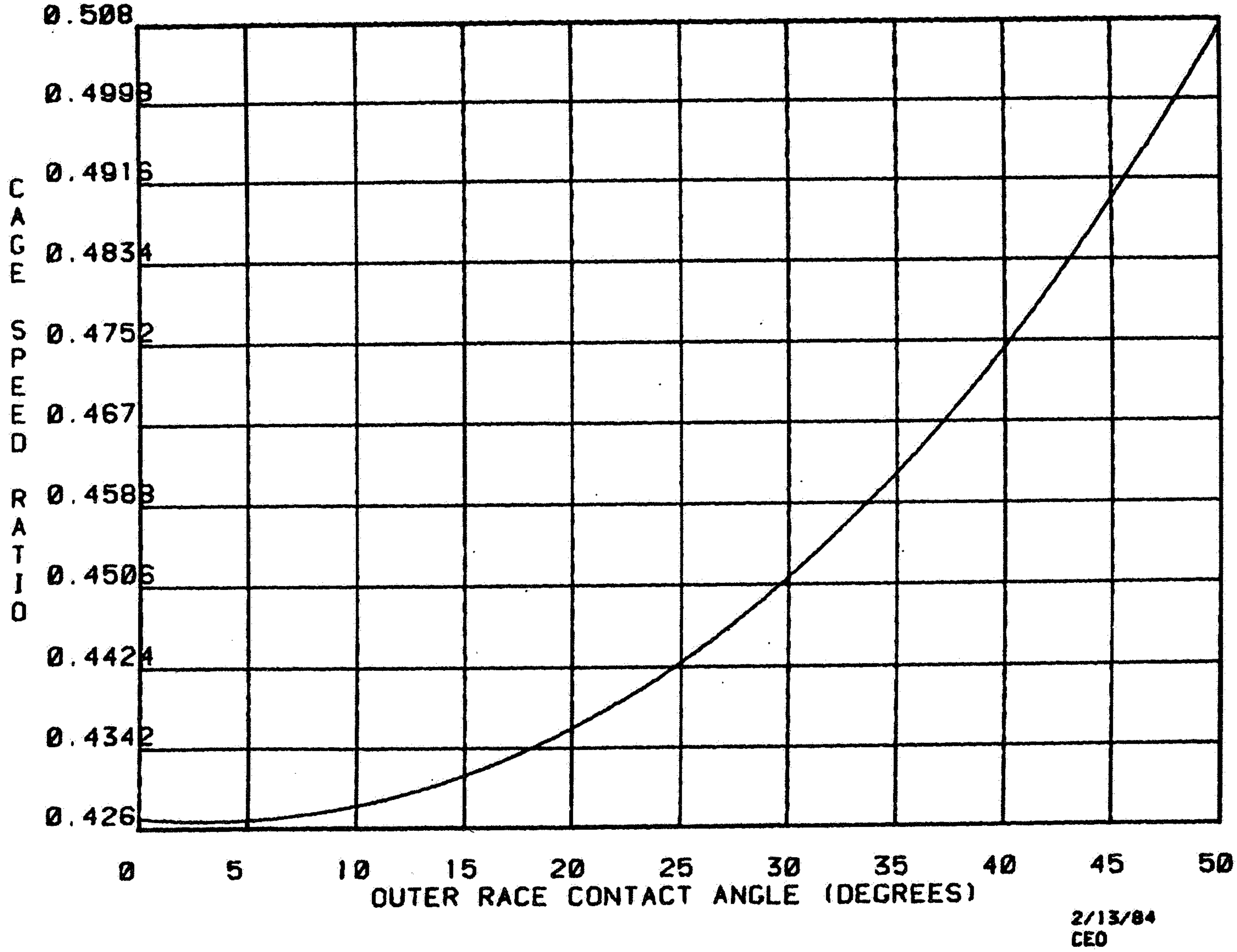



HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE SPEED RATIO
7.61
7.508
7.406
7.304
7.202
7.1
6.998
6.896
6.794
6.692
6.59
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
INNER RACE CONTACT ANGLE
40
30
.35
...25
20
...15
10
...5
3
2/13/84
CEO

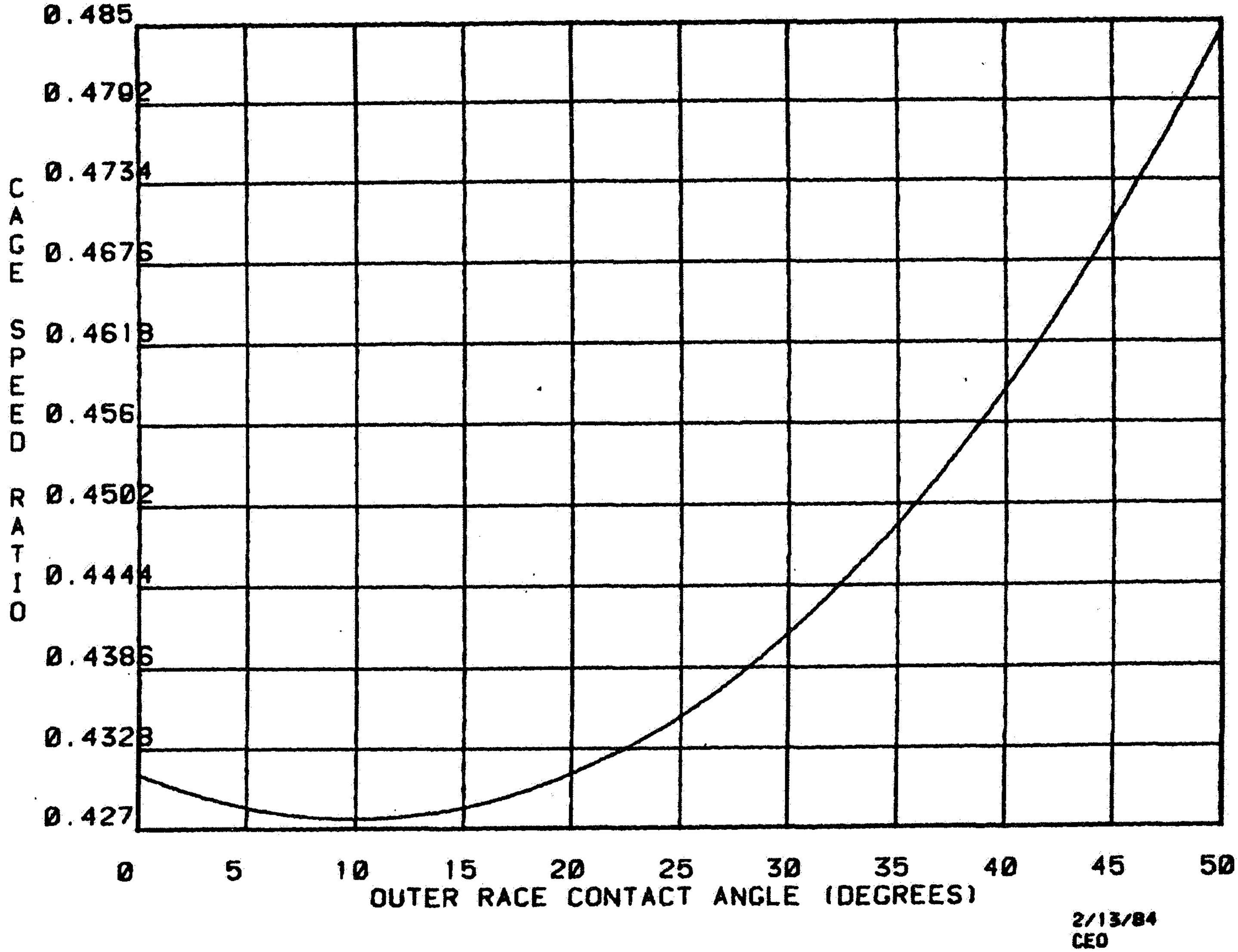
SPEED RATIO OF
HPFTP PUMP AND TURBINE BEARINGS
3-, 10-, 20-, AND 30-DEGREE α_i
(Inner Race Contact Angle)

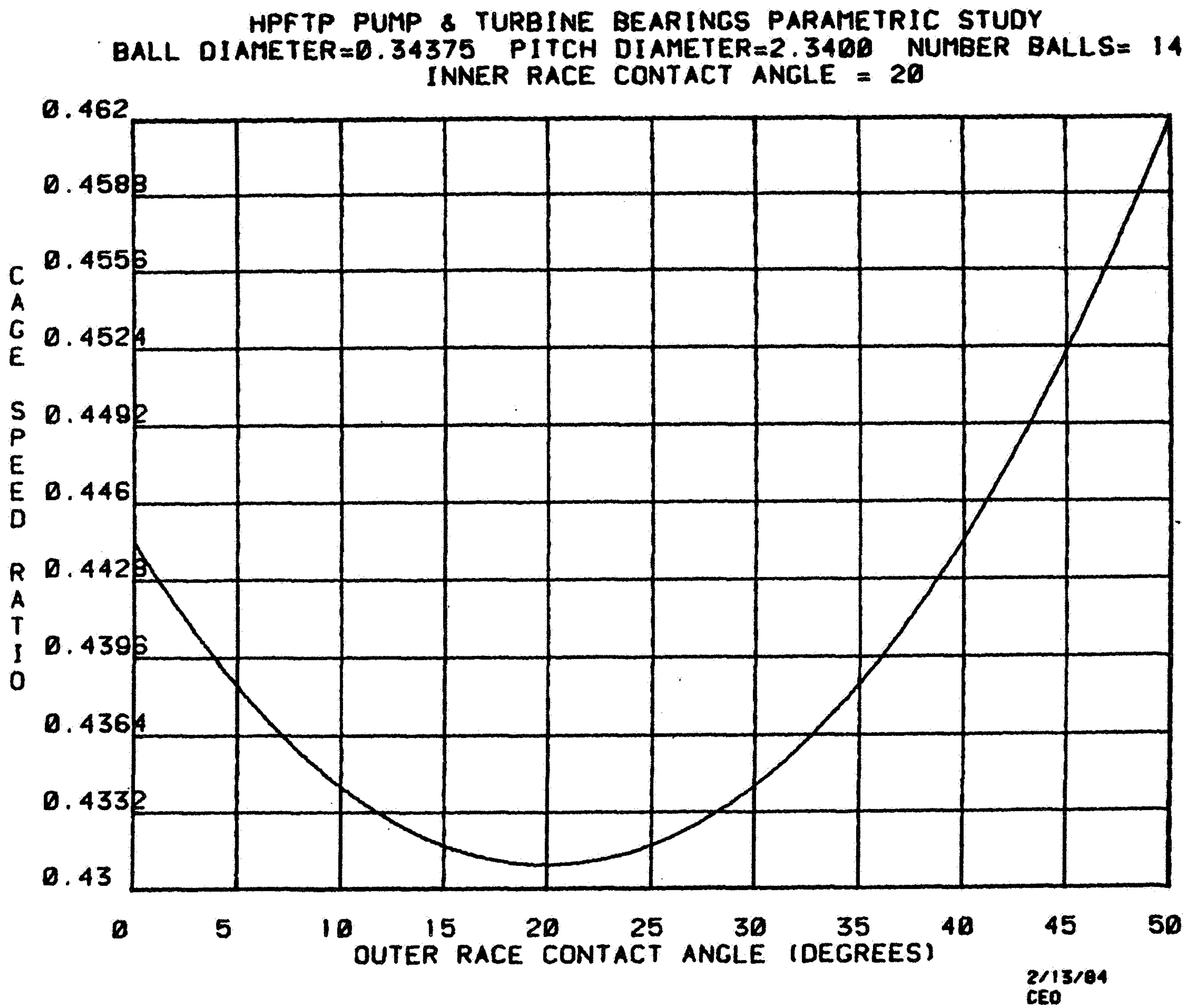
Ball Diameter = 0.343750 inch
Pitch Diameter = 2.34 inches
Number of Balls = 14

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 3

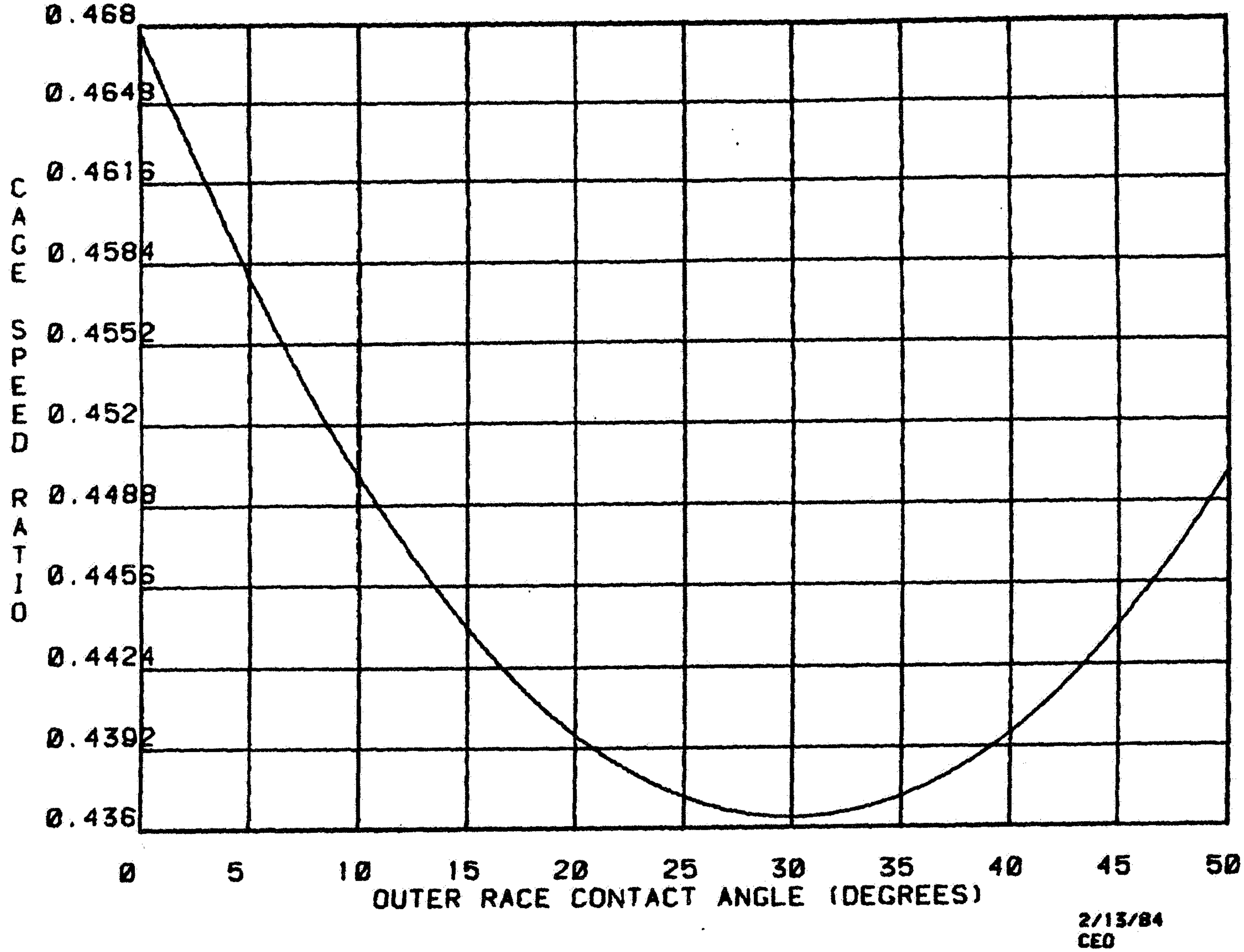


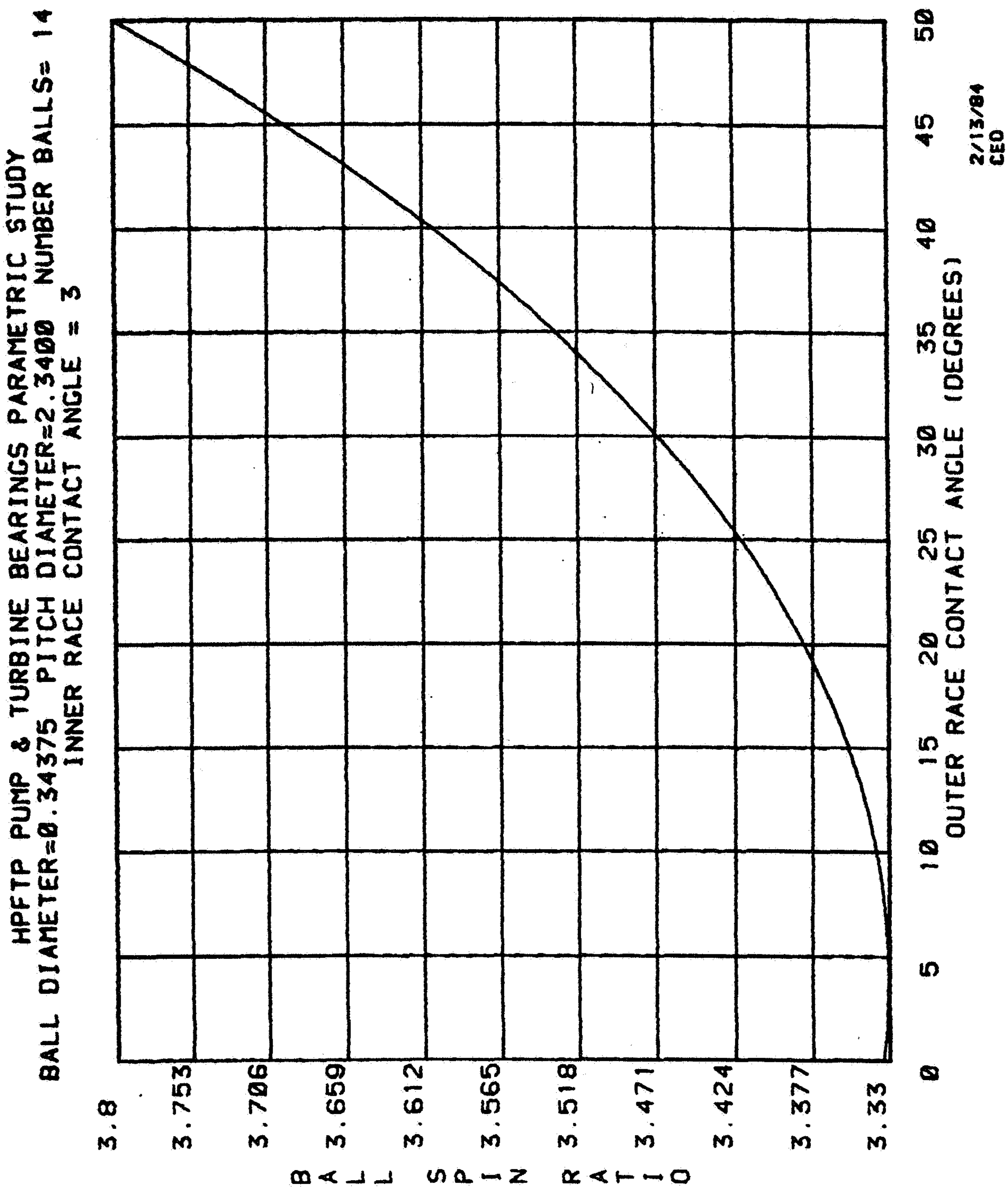
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 10

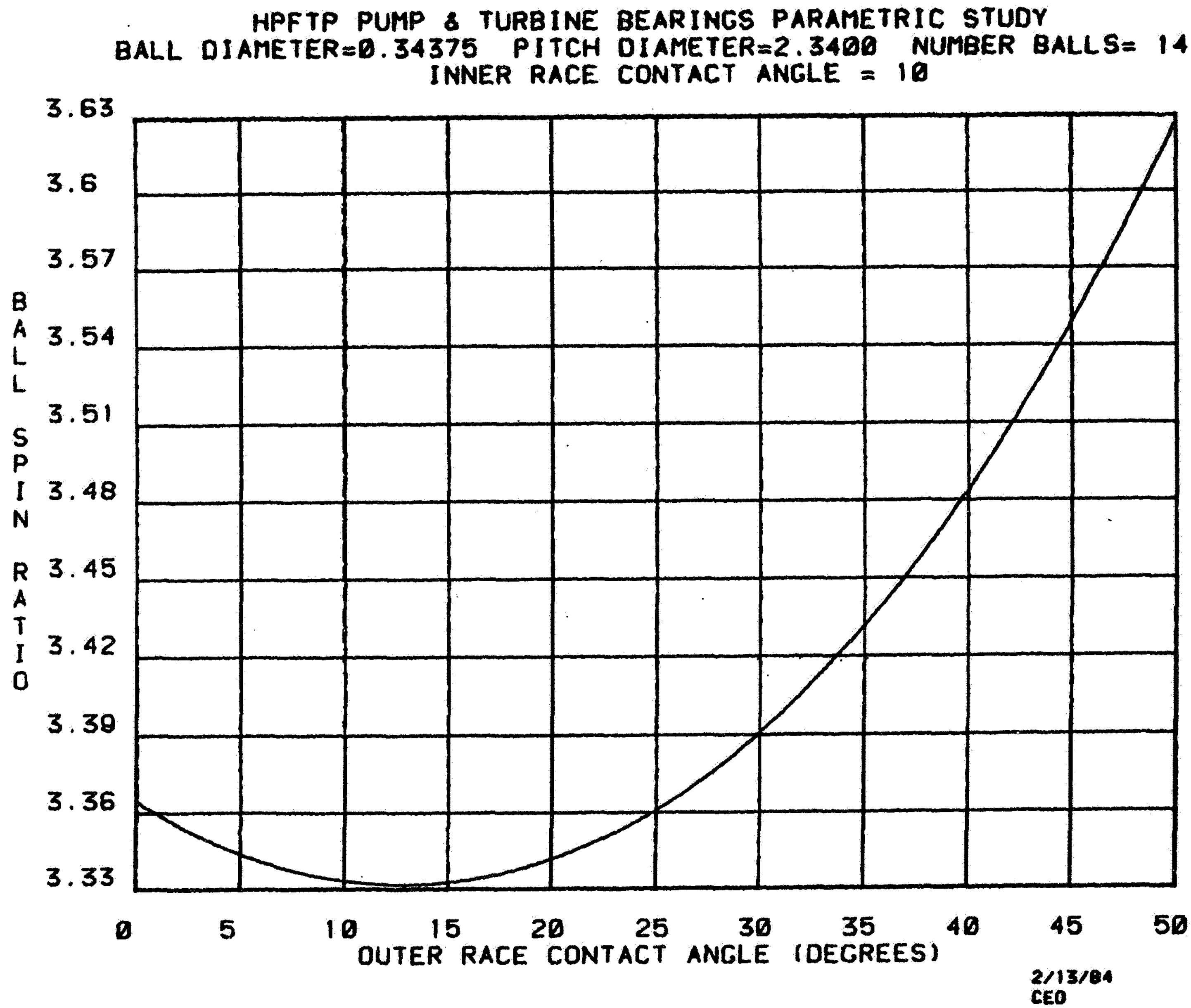



HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 20
CAGE SPEED RATIO
0.462
0.4588
0.4556
0.4524
0.4492
0.446
0.4428
0.4396
0.4364
0.4332
0.43
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

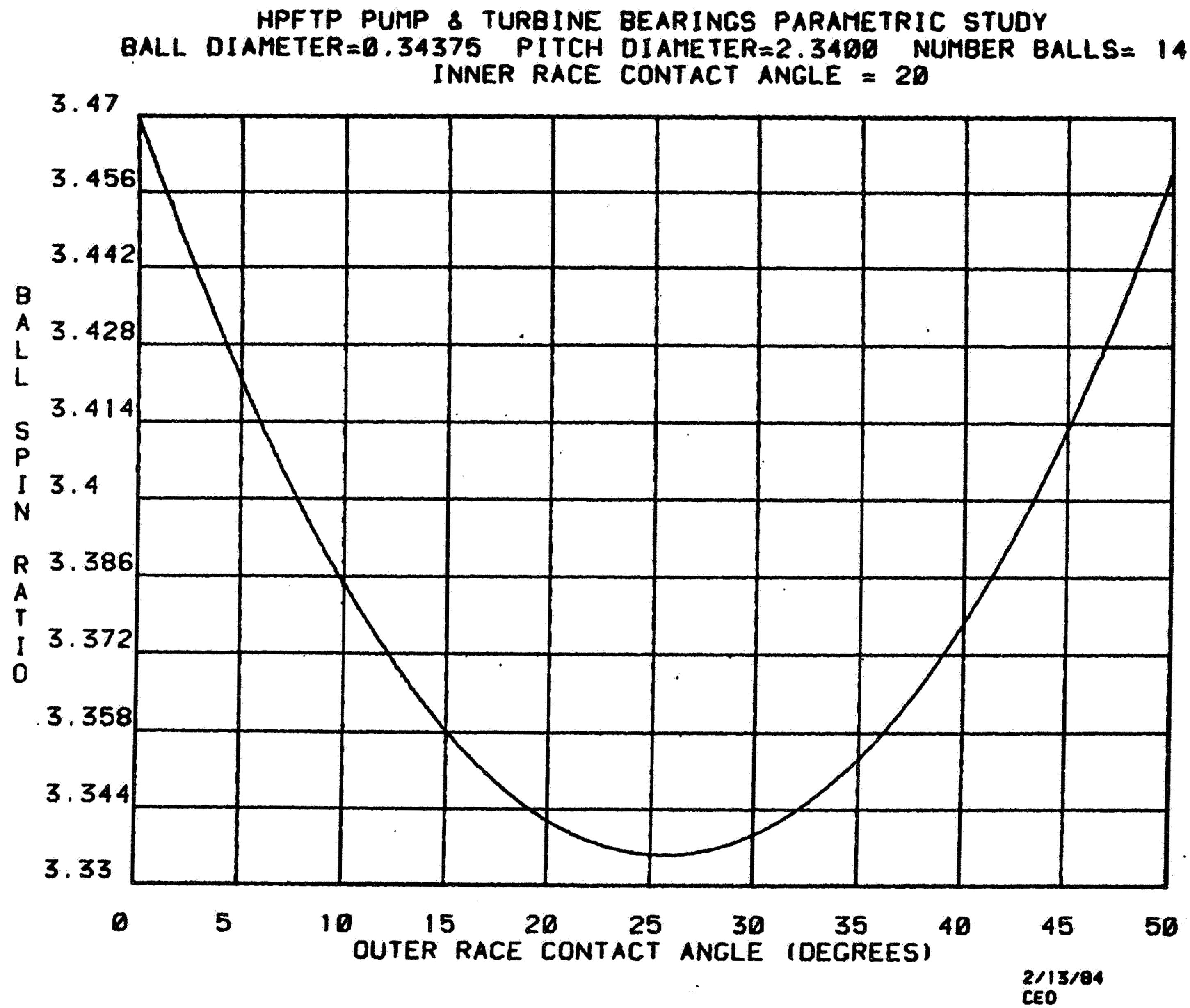
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 30

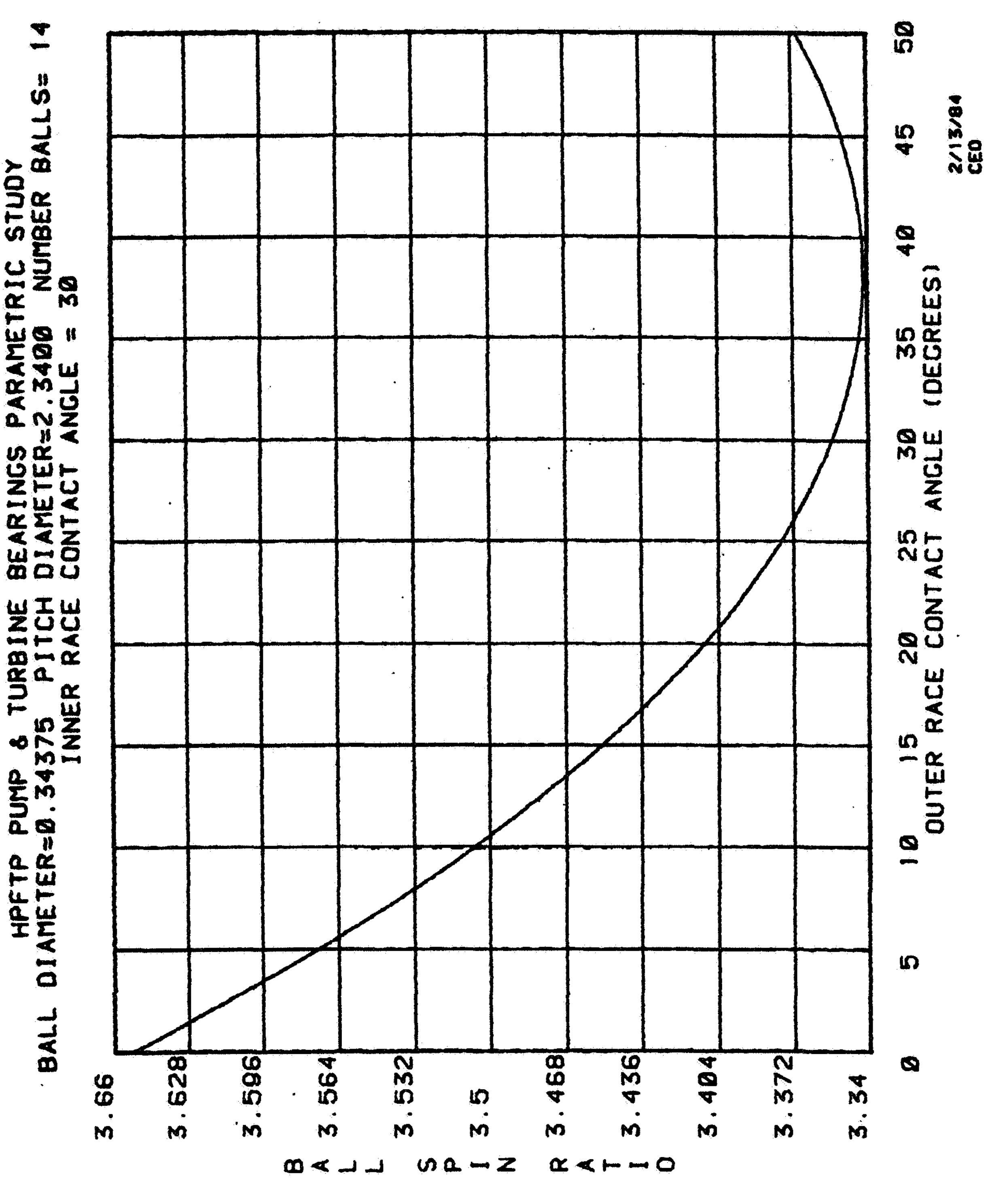



HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 3
BALL SPIN RATIO
3.8
3.753
3.706
3.659
3.612
3.565
3.518
3.471
3.424
3.377
3.33
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

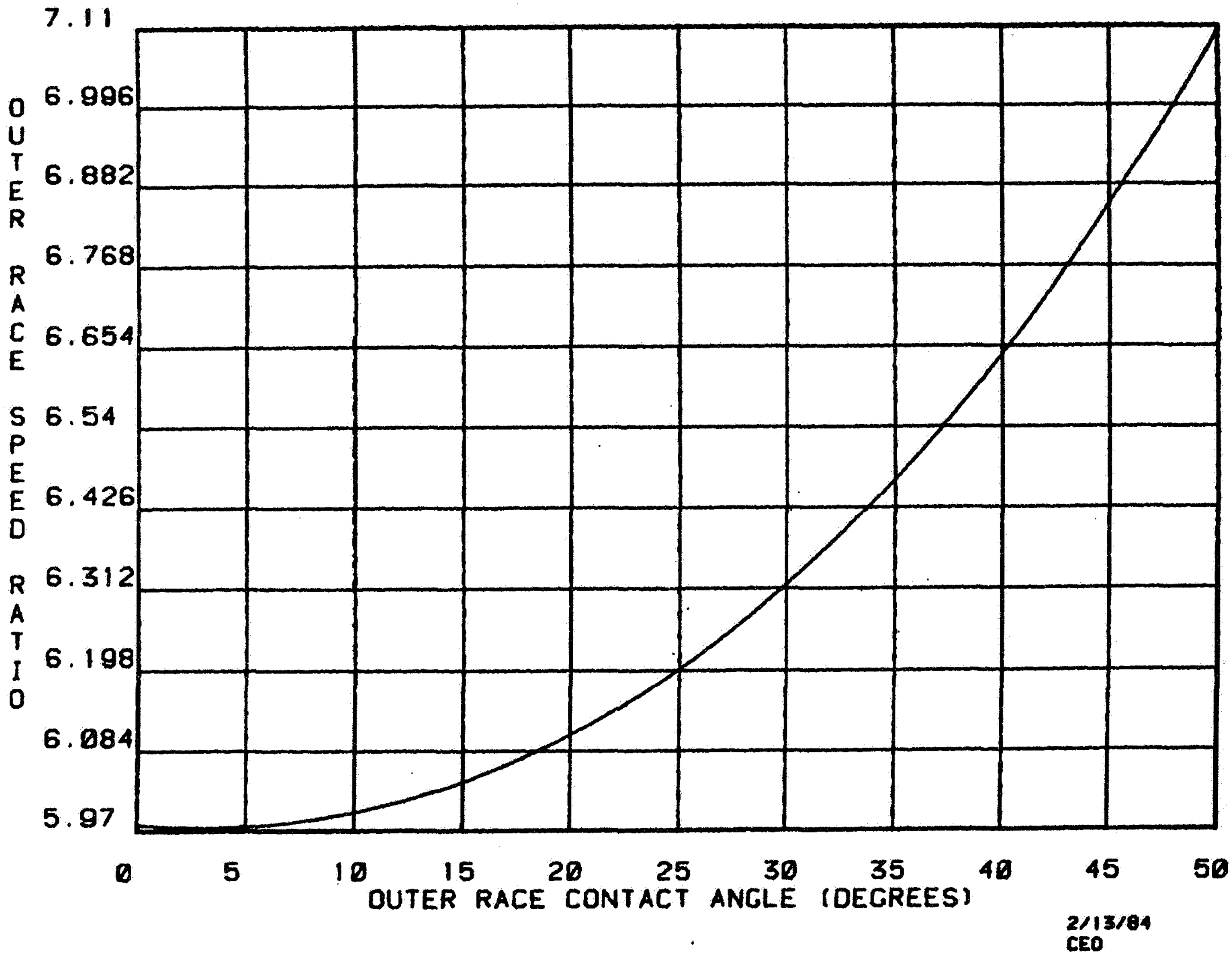


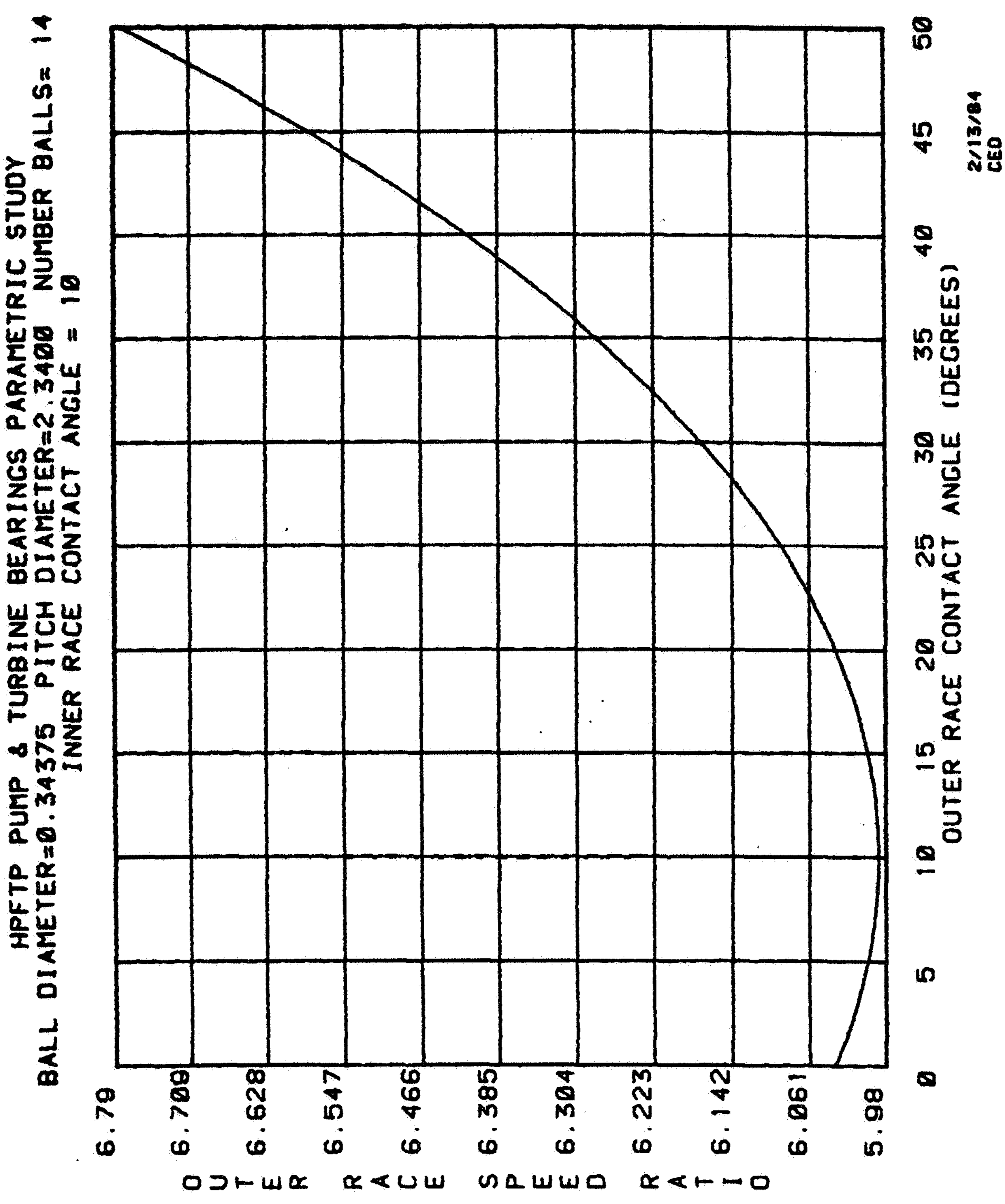
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 10
BALL SPIN RATIO
3.63
3.6
3.57
3.54
3.51
3.48
3.45
3.42
3.39
3.36
3.33
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO


HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 20
BALL SPIN RATIO
3.47
3.456
3.442
3.428
3.414
3.4
3.386
3.372
3.358
3.344
3.33
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

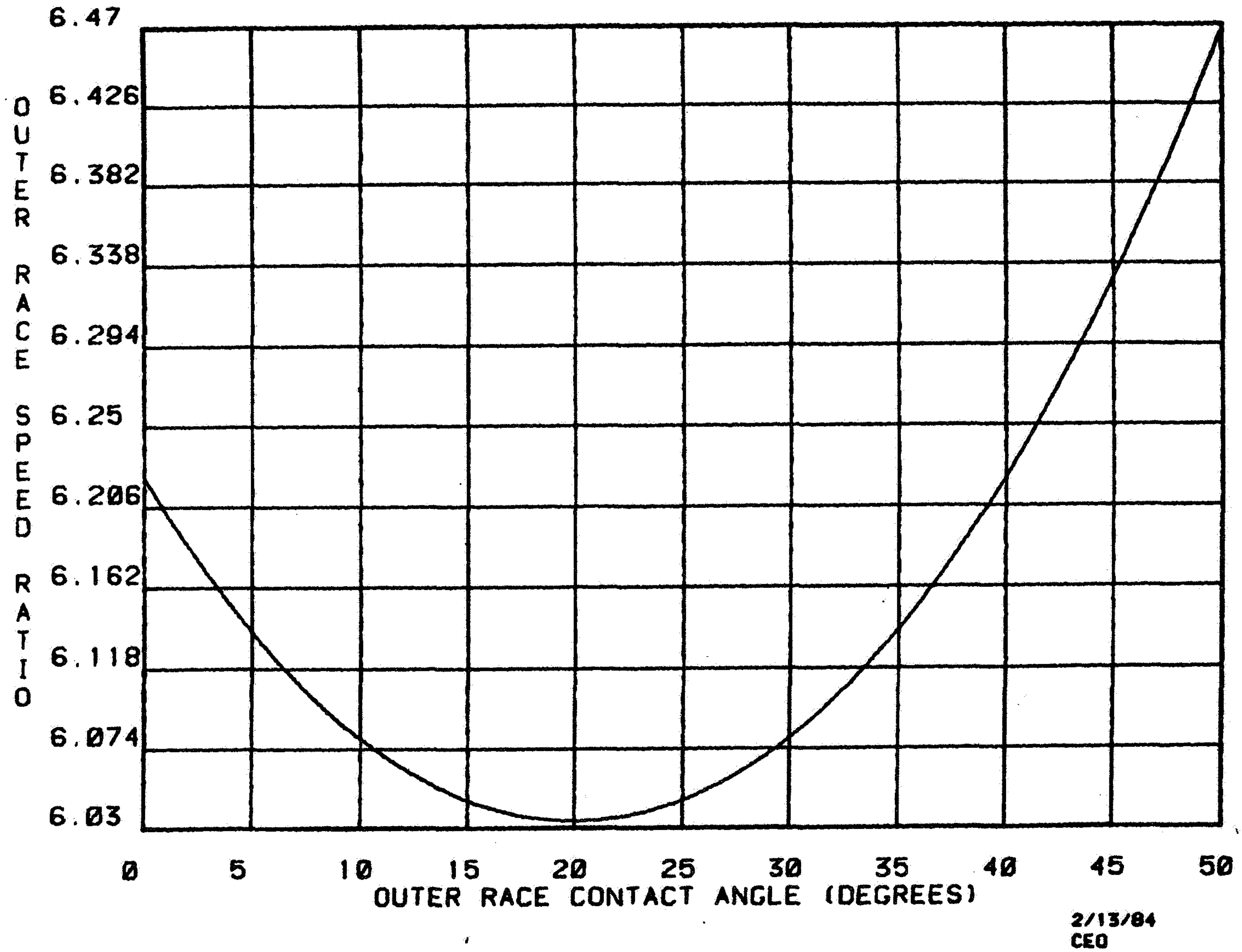

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 30
BALL SPIN RATIO
3.66
3.628
3.596
3.564
3.532
3.5
3.468
3.436
3.404
3.372
3.34
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

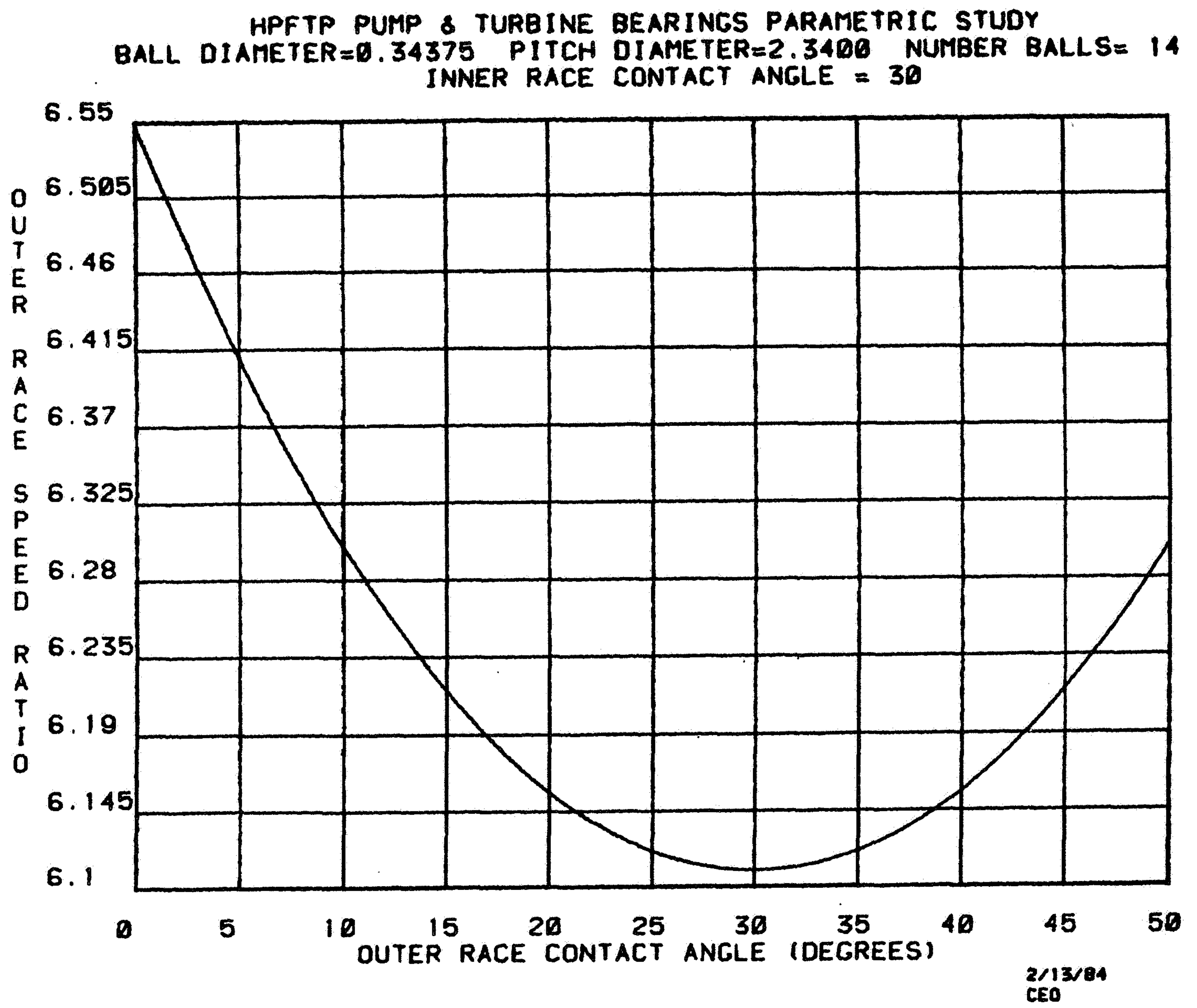
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 3

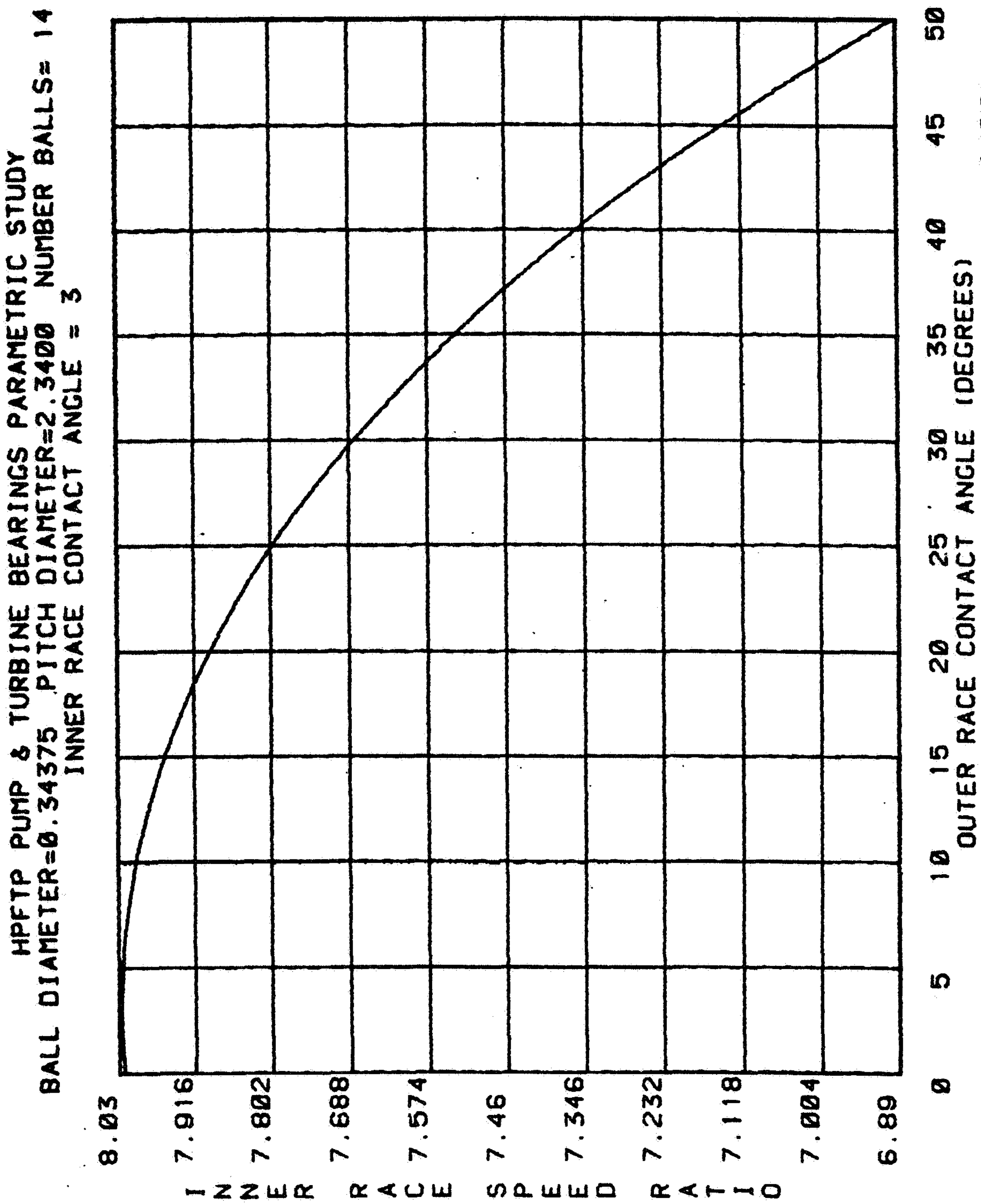



HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 10
OUTER RACE SPEED RATIO
6.79
6.709
6.628
6.547
6.466
6.385
6.304
6.223
6.142
6.061
5.98
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

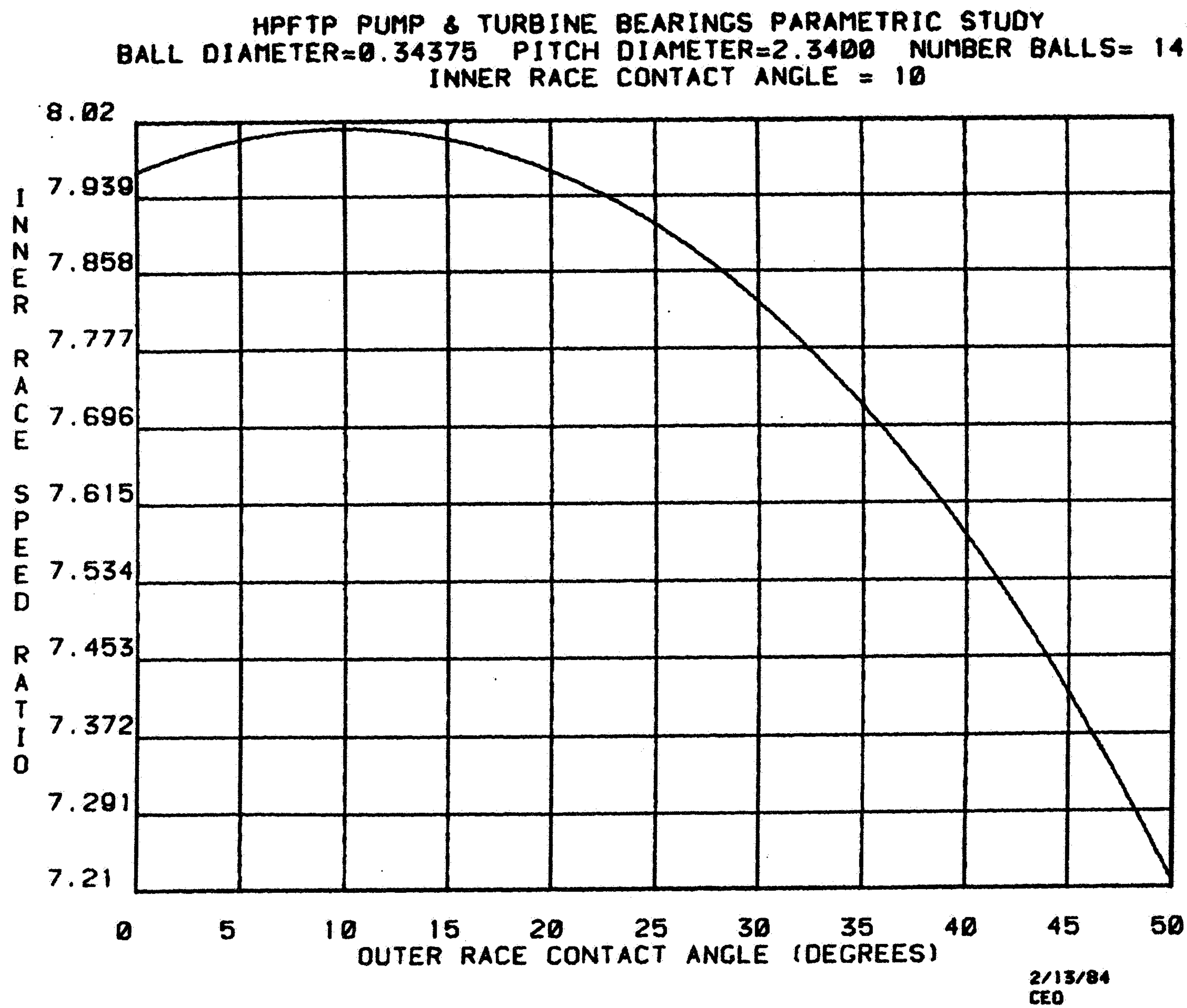
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 20



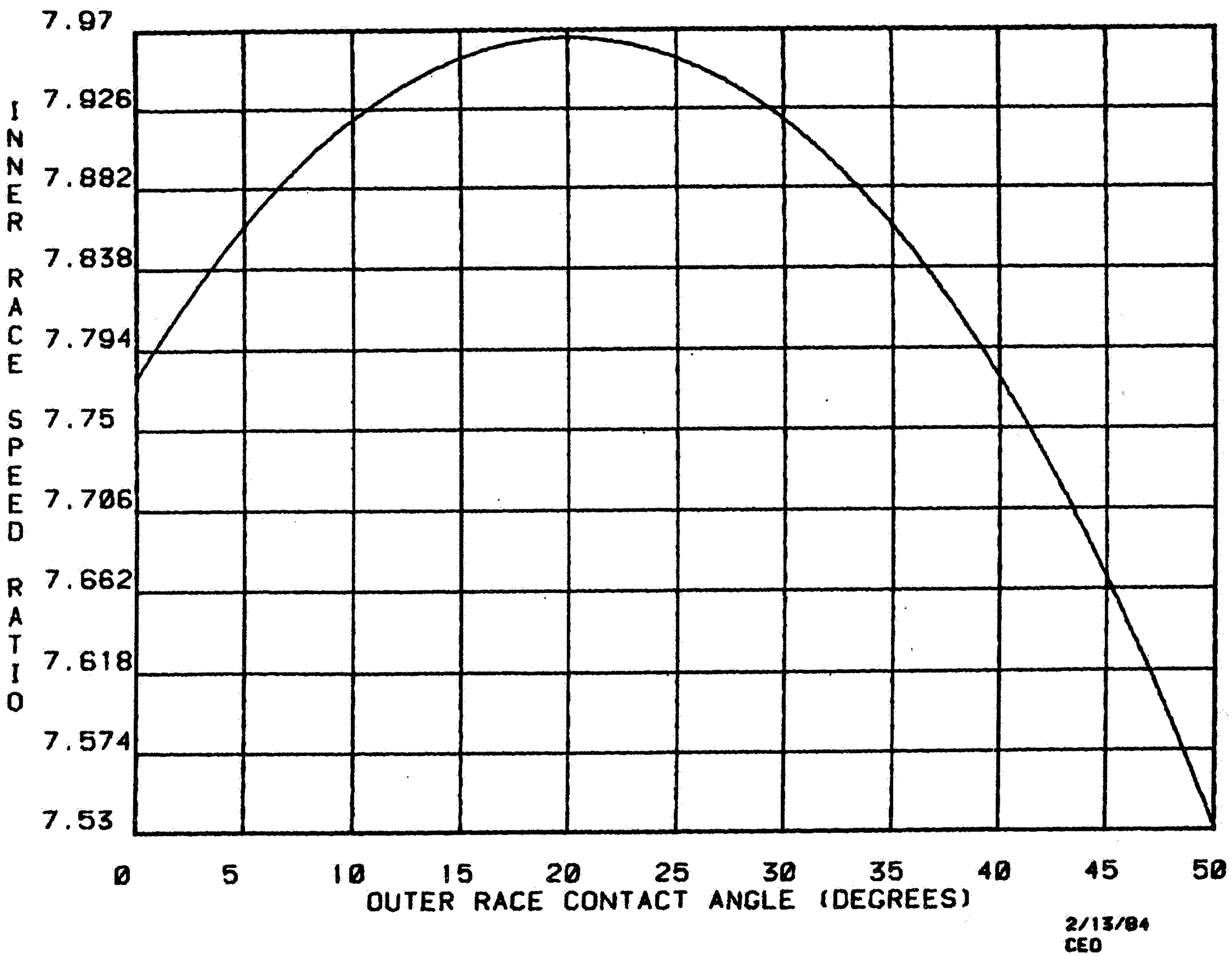

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 30
6.55
6.505
6.46
6.415
6.37
6.325
6.28
6.235
6.19
6.145
6.1
OUTER RACE SPEED RATIO
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO



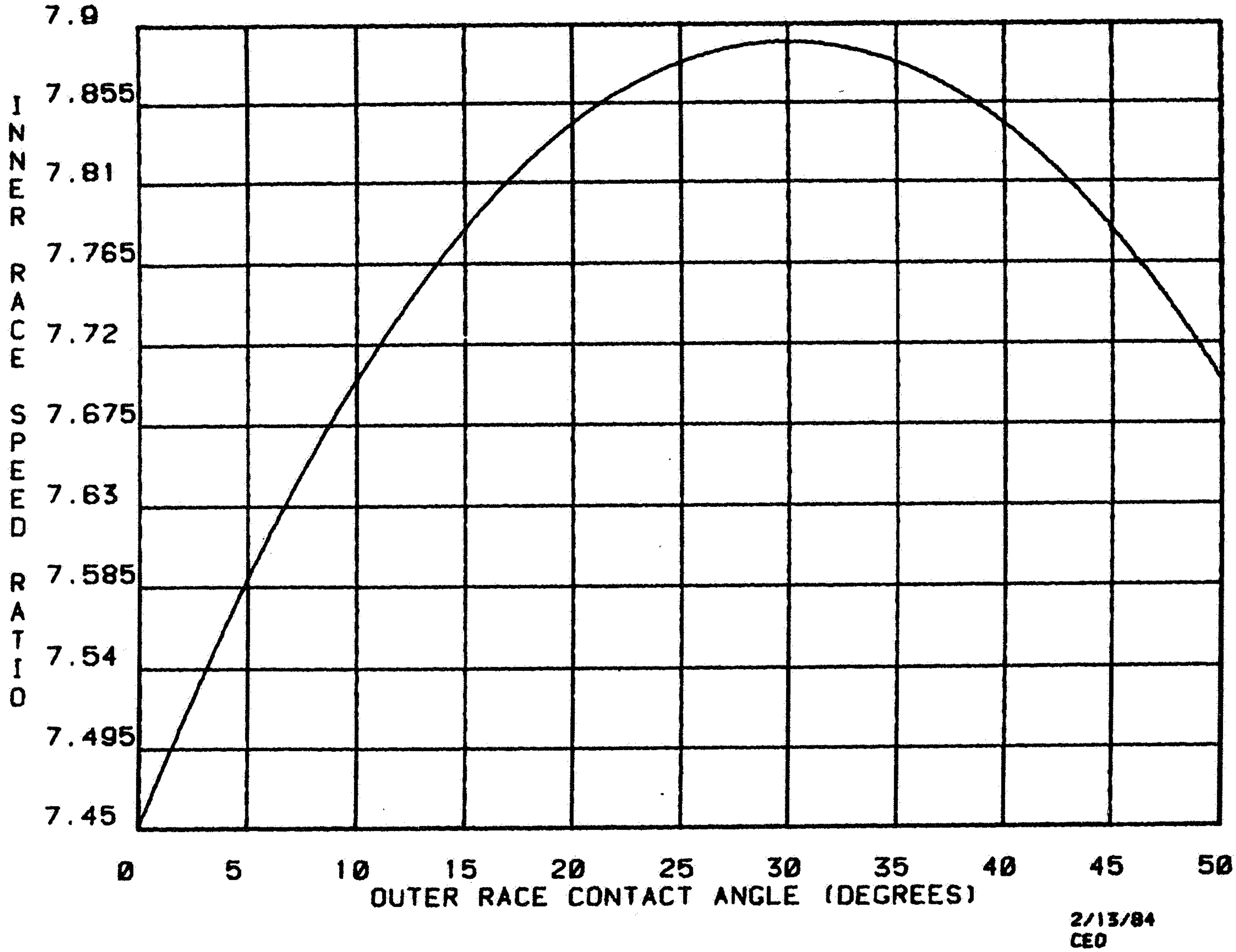
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 3
INNER RACE SPEED RATIO
8.03
7.916
7.802
7.688
7.574
7.46
7.346
7.232
7.118
7.004
6.89
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO


HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 10
INNER RACE SPEED RATIO
8.02
7.939
7.858
7.777
7.696
7.615
7.534
7.453
7.372
7.291
7.21
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 20

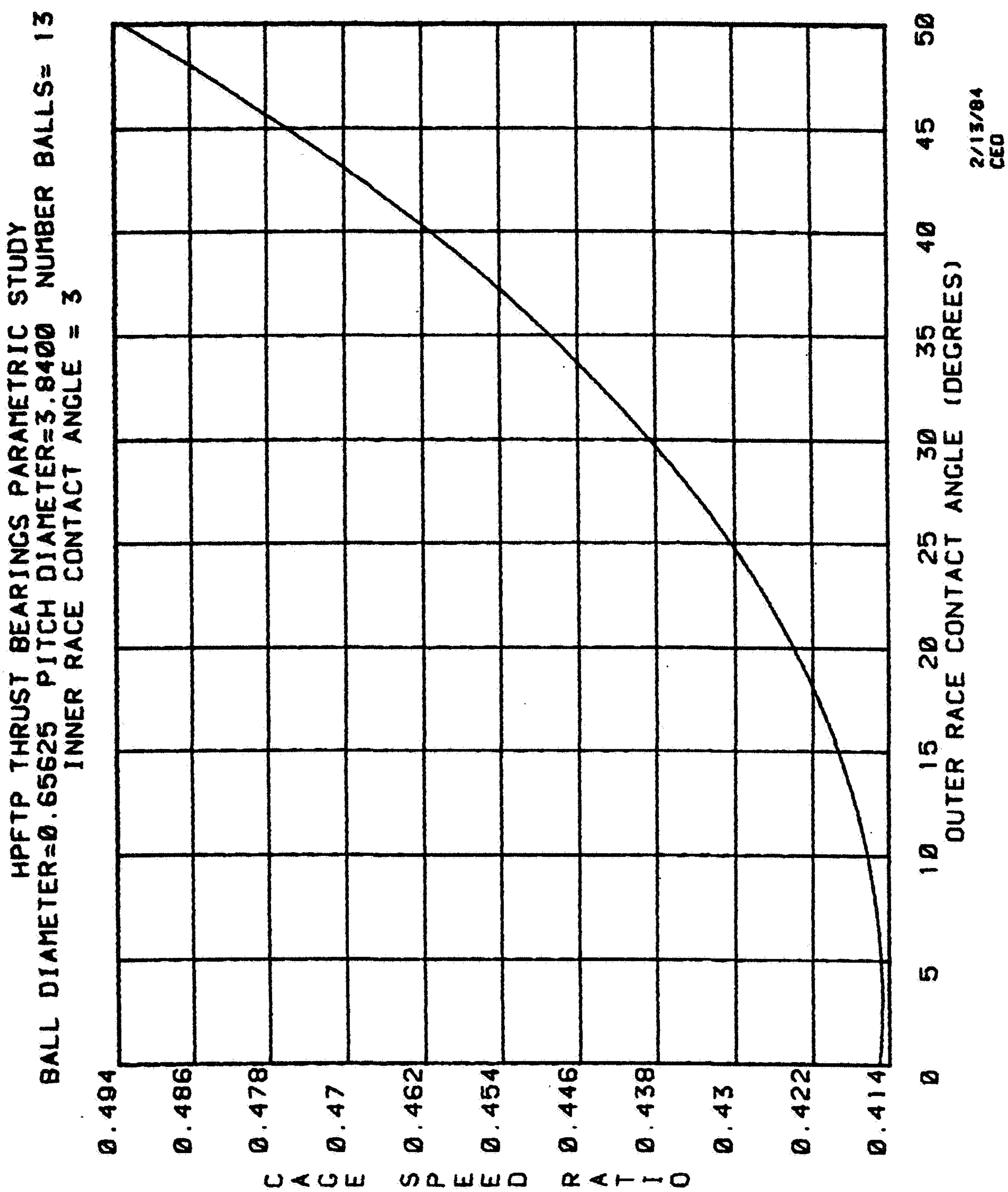


HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER RACE CONTACT ANGLE = 30

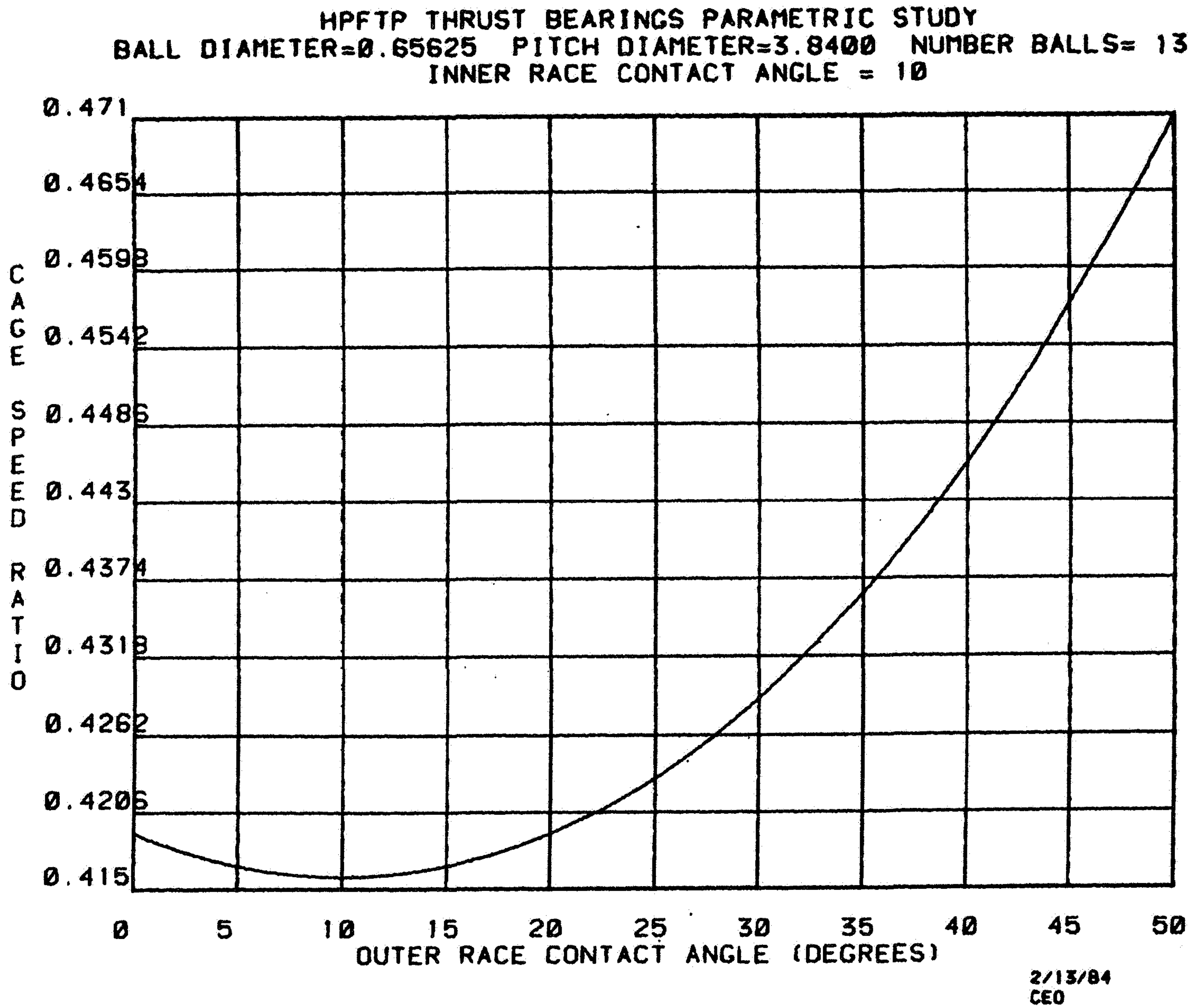


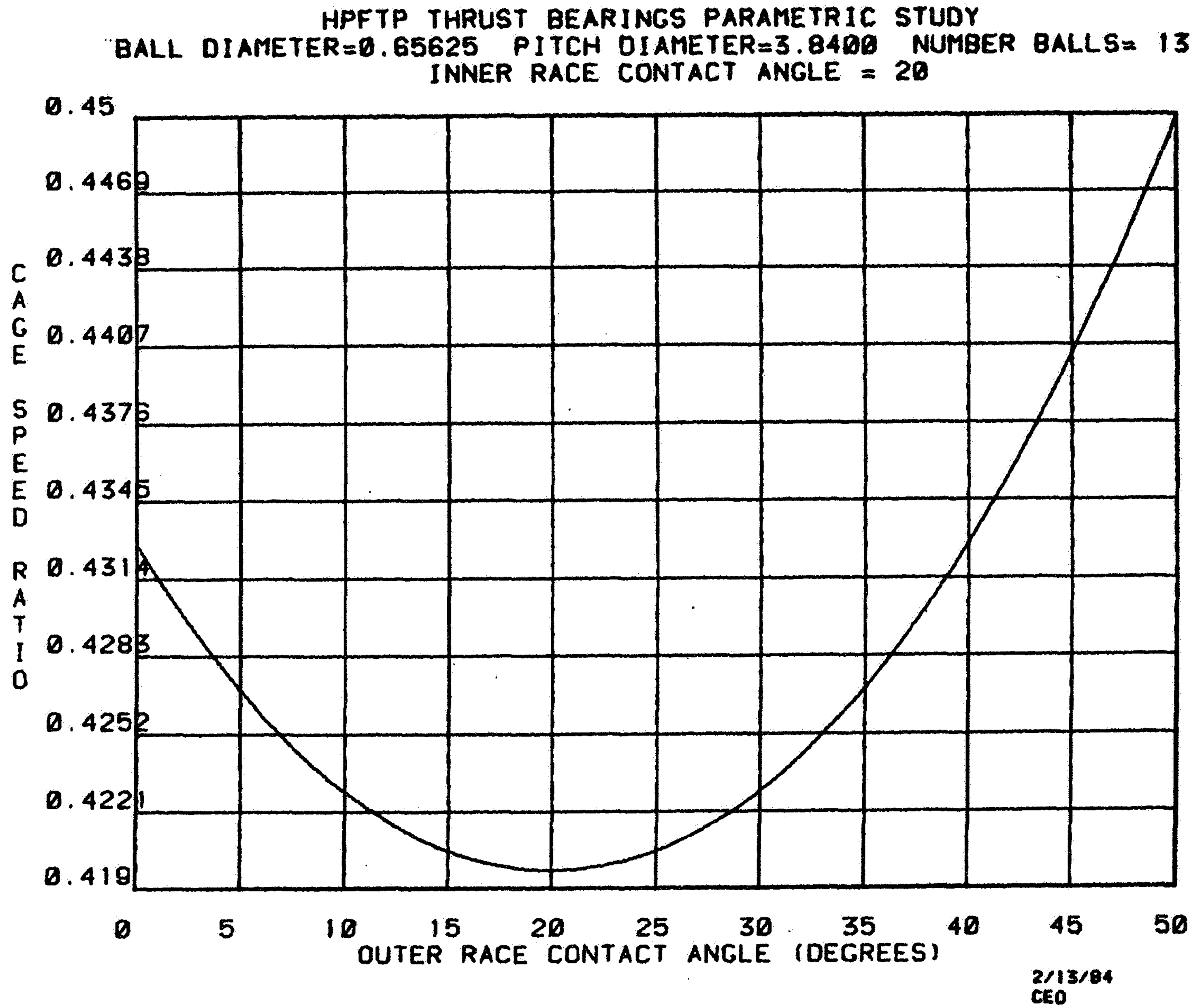
SPEED RATIO OF
HPFTP THRUST BEARINGS
3-, 10-, 20-, AND 30-DEGREE α_i
(Inner Race Contact Angle)

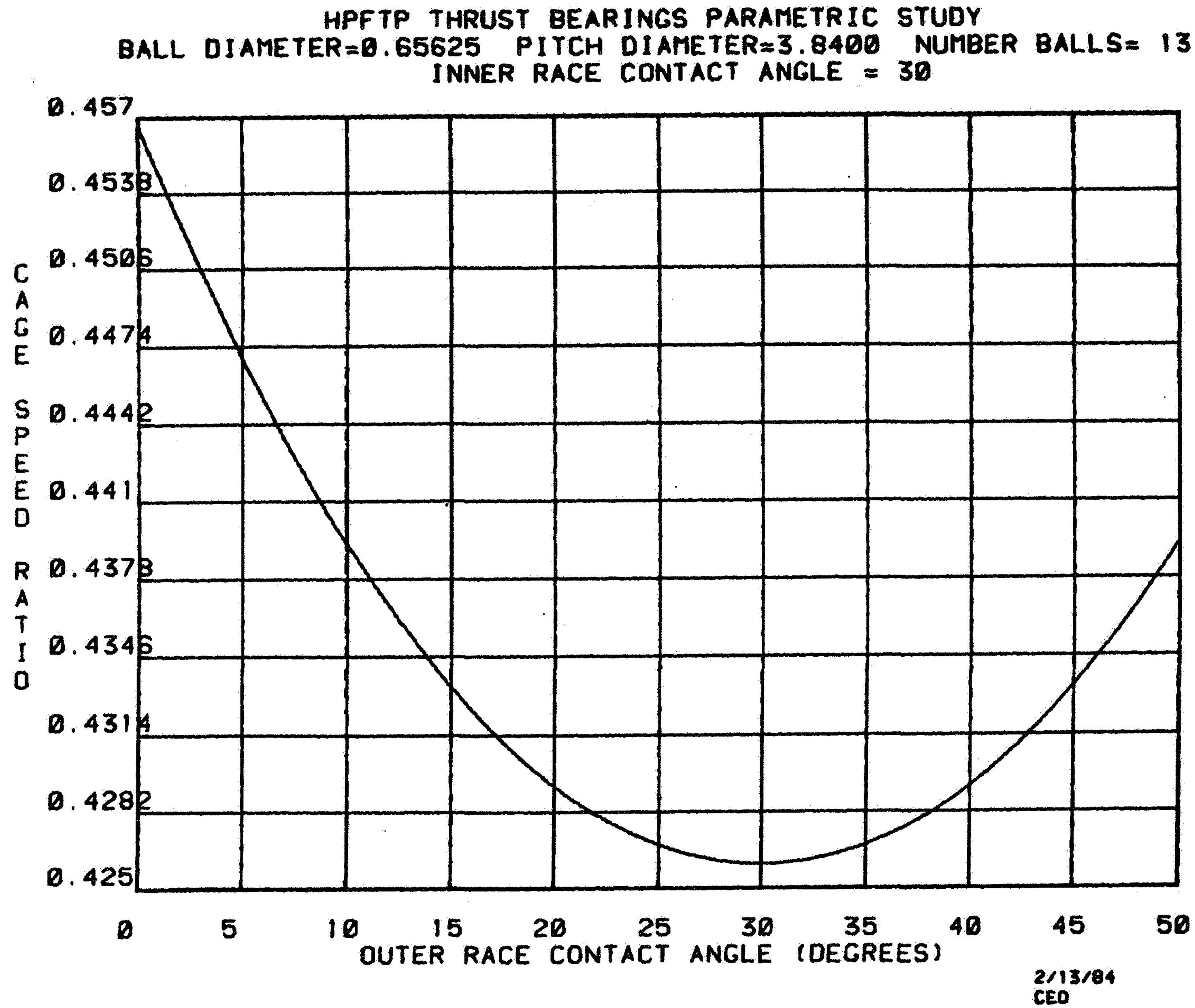
Ball Diameter = 0.656250 inch
Pitch Diameter = 3.84 inches
Number of Balls = 13

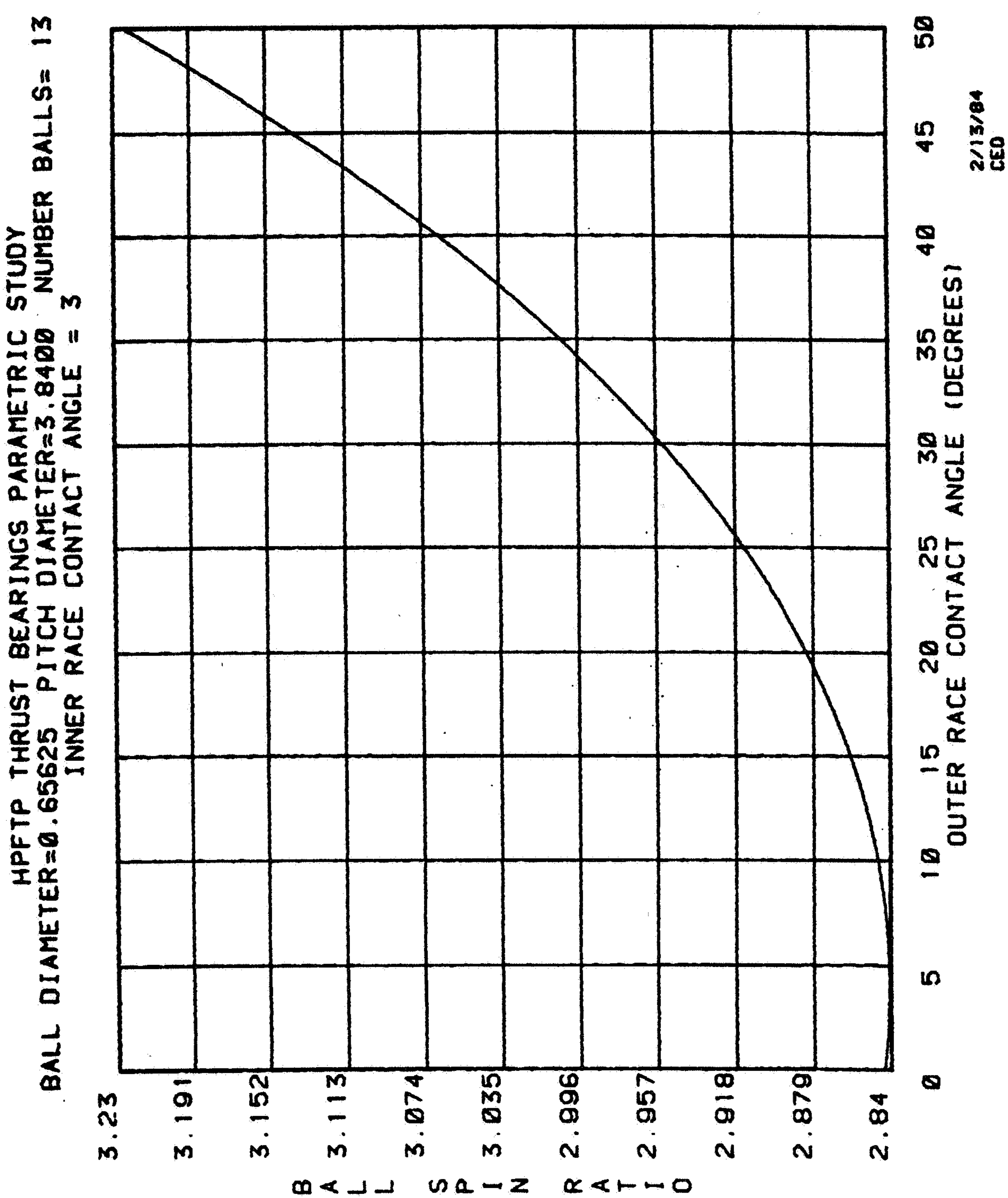


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
CAGE SPEED RATIO
0.494
0.486
0.478
0.47
0.462
0.454
0.446
0.438
0.43
0.422
0.414
0 5 10 15 20 25 30 35 40 45 50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

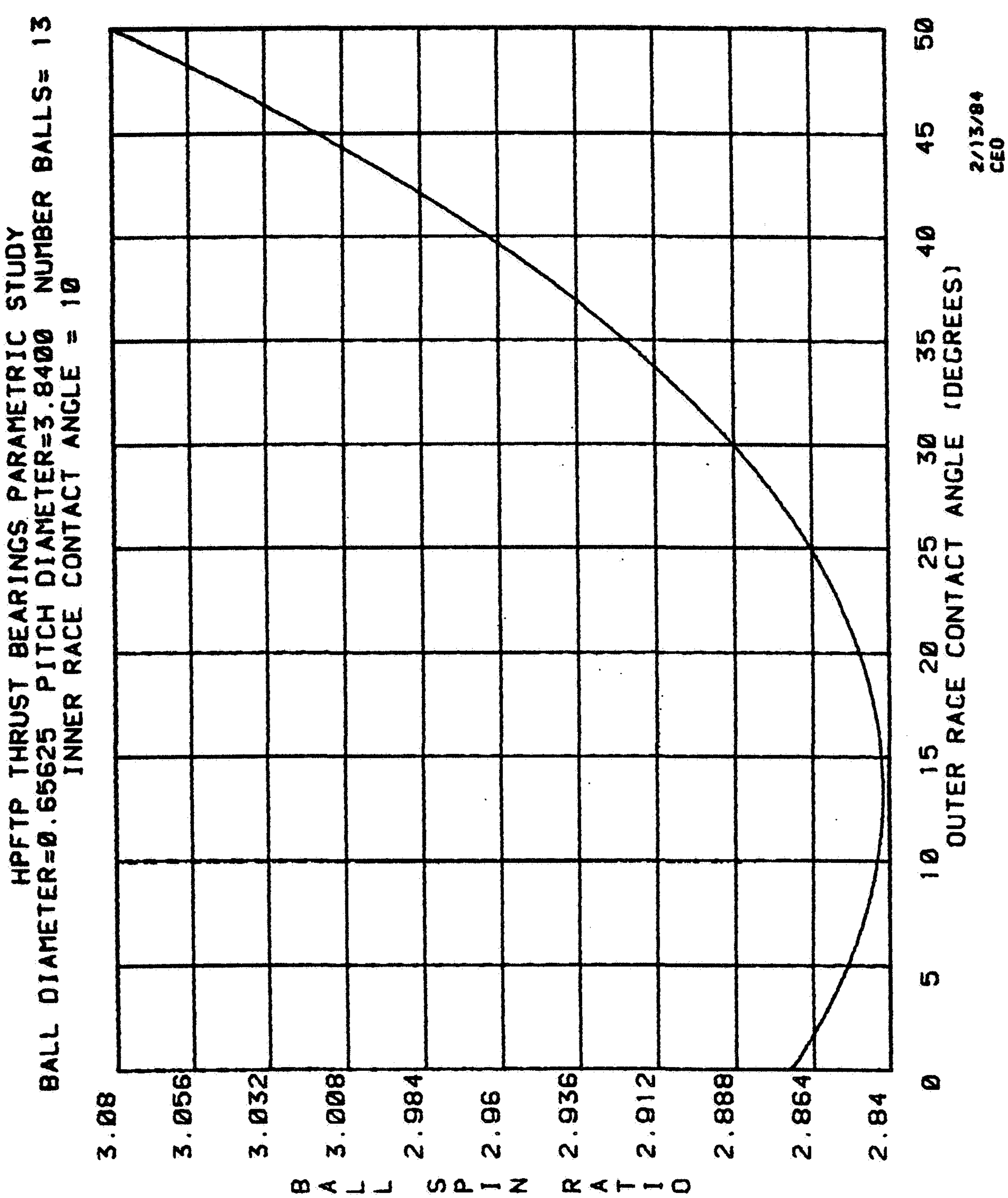

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
CAGE SPEED RATIO
0.471
0.4654
0.4598
0.4542
0.4486
0.443
0.4374
0.4318
0.4262
0.4206
0.415
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

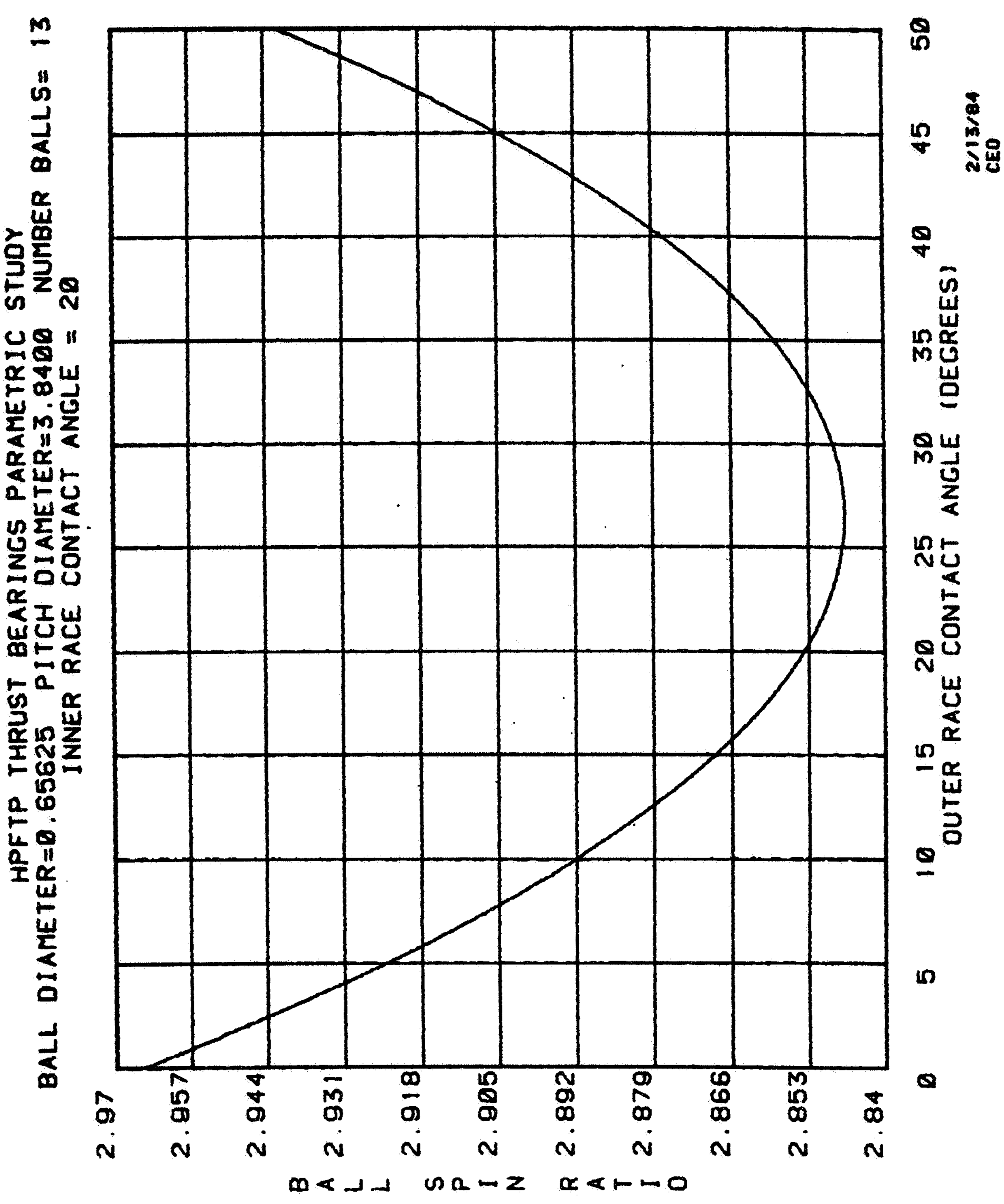

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
CAGE SPEED RATIO
0.45
0.4469
0.4438
0.4407
0.4376
0.4345
0.4314
0.4283
0.4252
0.4221
0.419
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

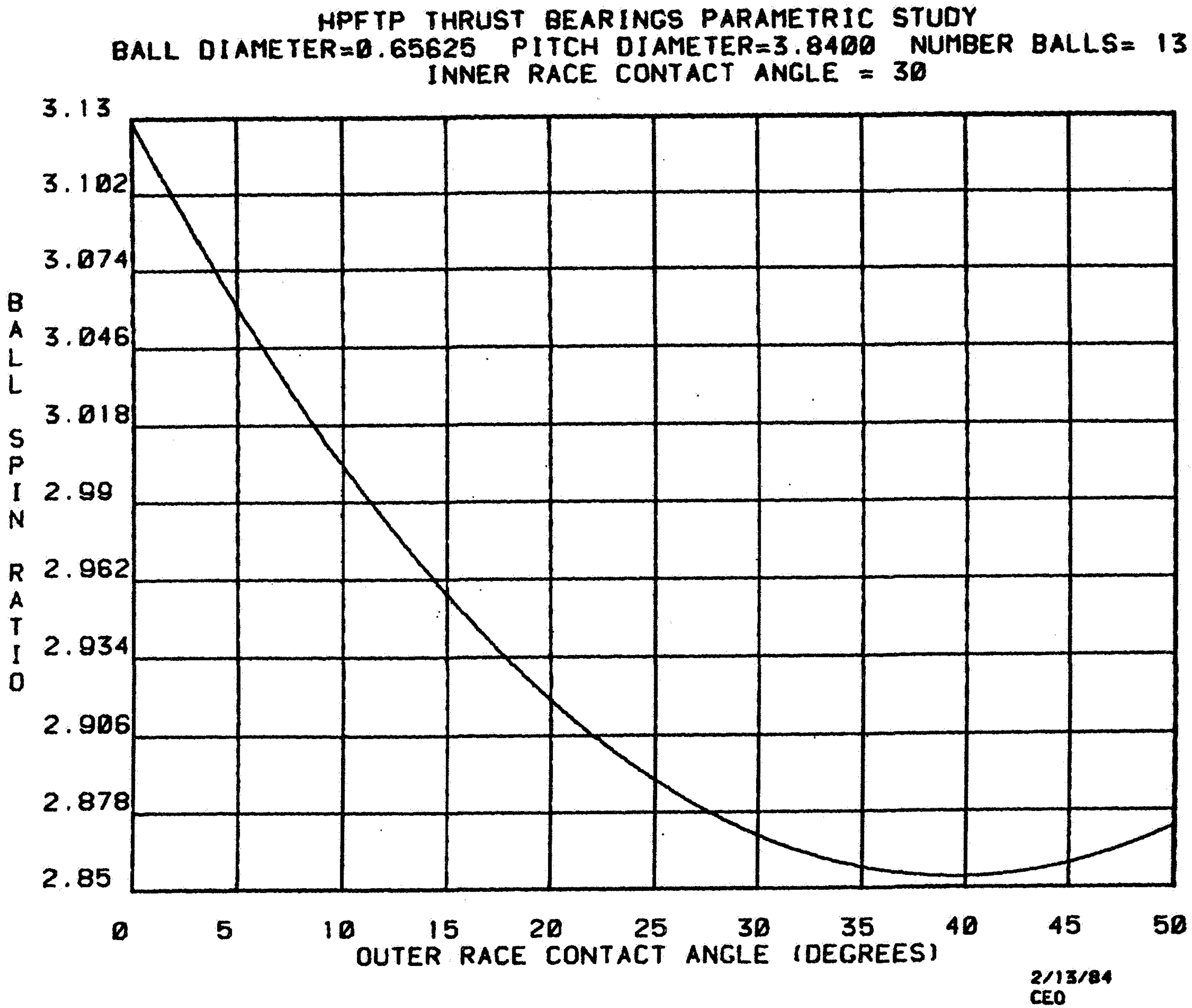

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
CAGE SPEED RATIO
0.457
0.4538
0.4506
0.4474
0.4442
0.441
0.4378
0.4346
0.4314
0.4282
0.425
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

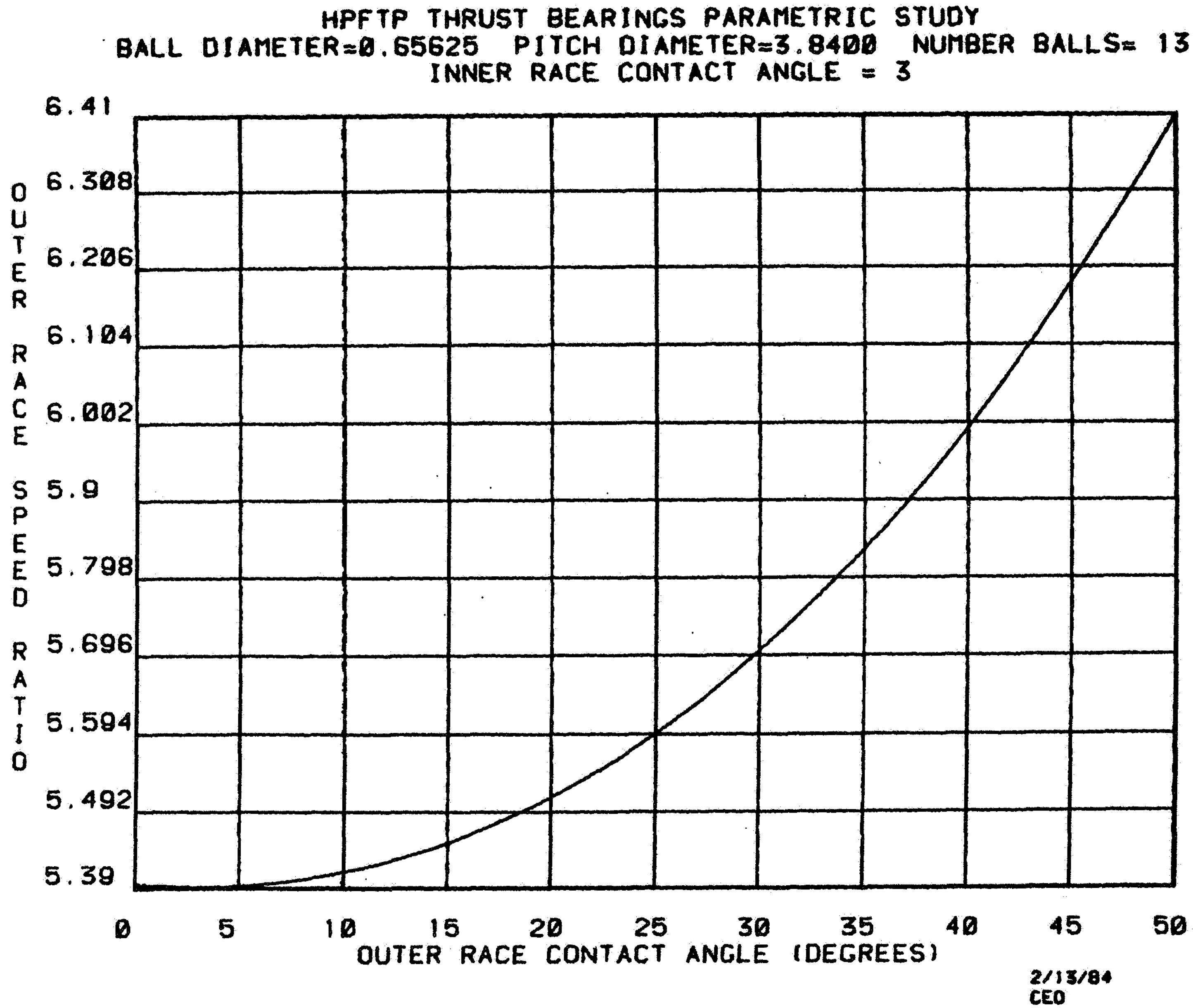


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
BALL SPIN RATIO
3.23
3.191
3.152
3.113
3.074
3.035
2.996
2.957
2.918
2.879
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

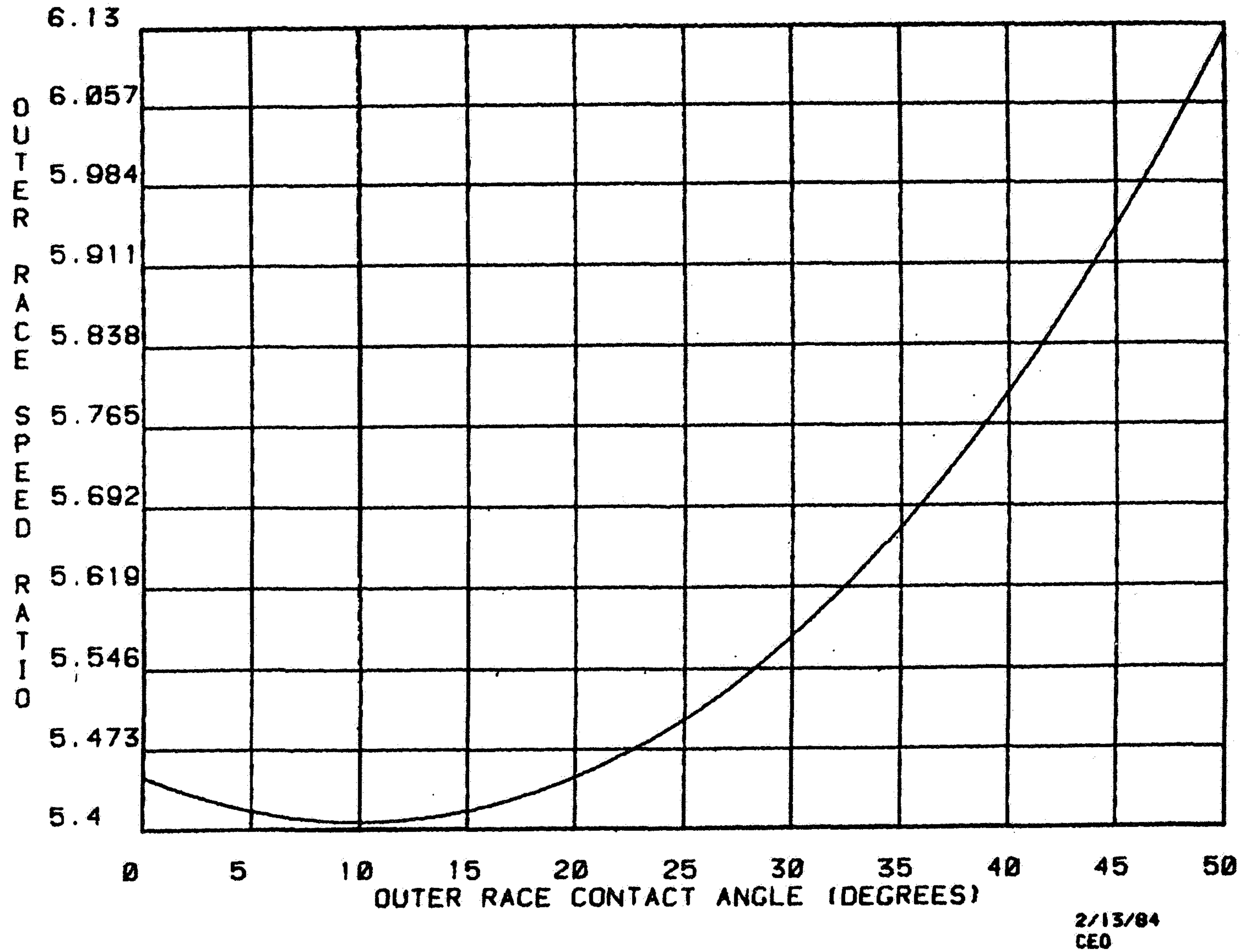

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
BALL SPIN RATIO
3.08
3.056
3.032
3.008
2.984
2.96
2.936
2.912
2.888
2.864
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
BALL SPIN RATIO
2.97
2.957
2.944
2.931
2.918
2.905
2.892
2.879
2.866
2.853
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

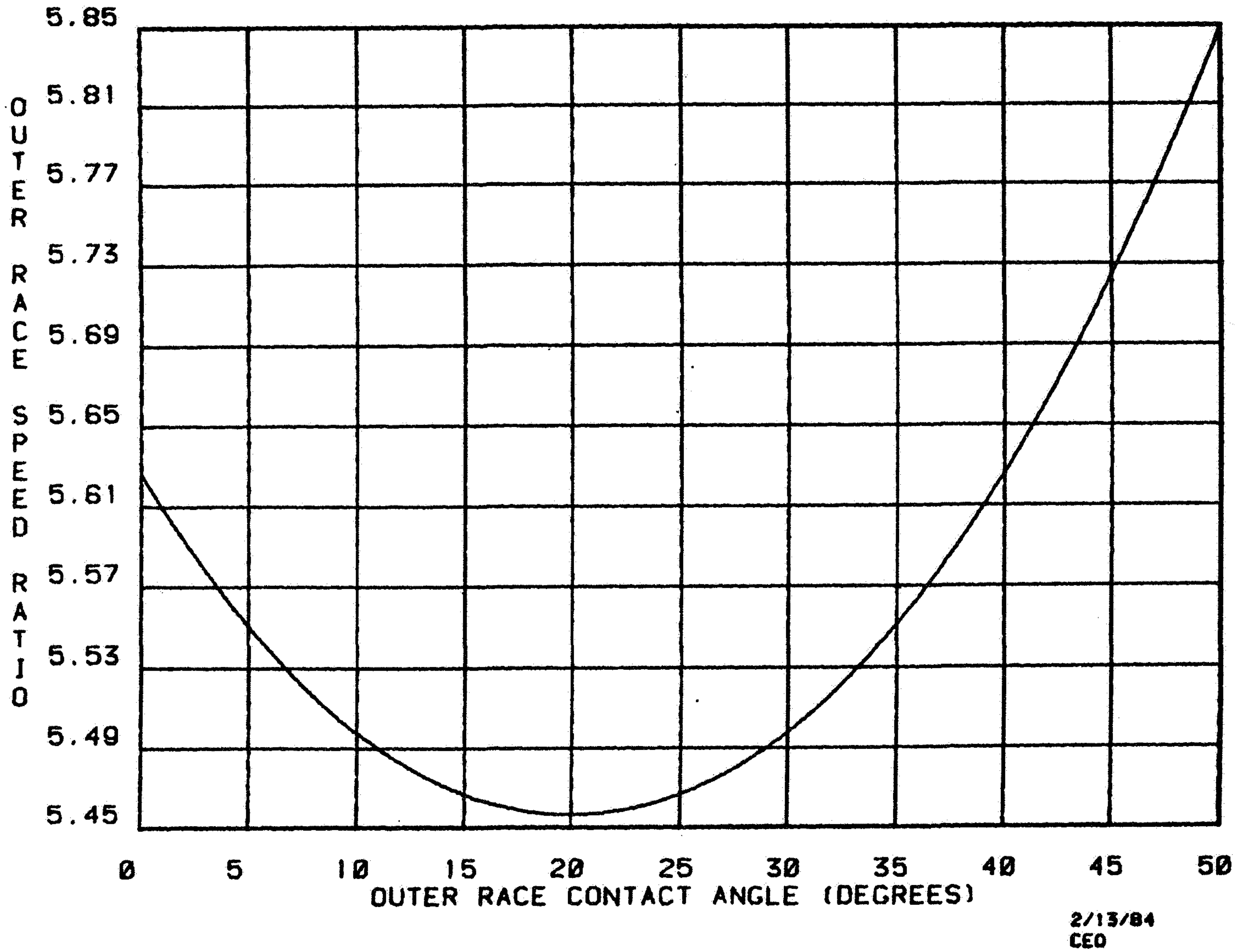

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
BALL SPIN RATIO
3.13
3.102
3.074
3.046
3.018
2.99
2.962
2.934
2.906
2.878
2.85
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

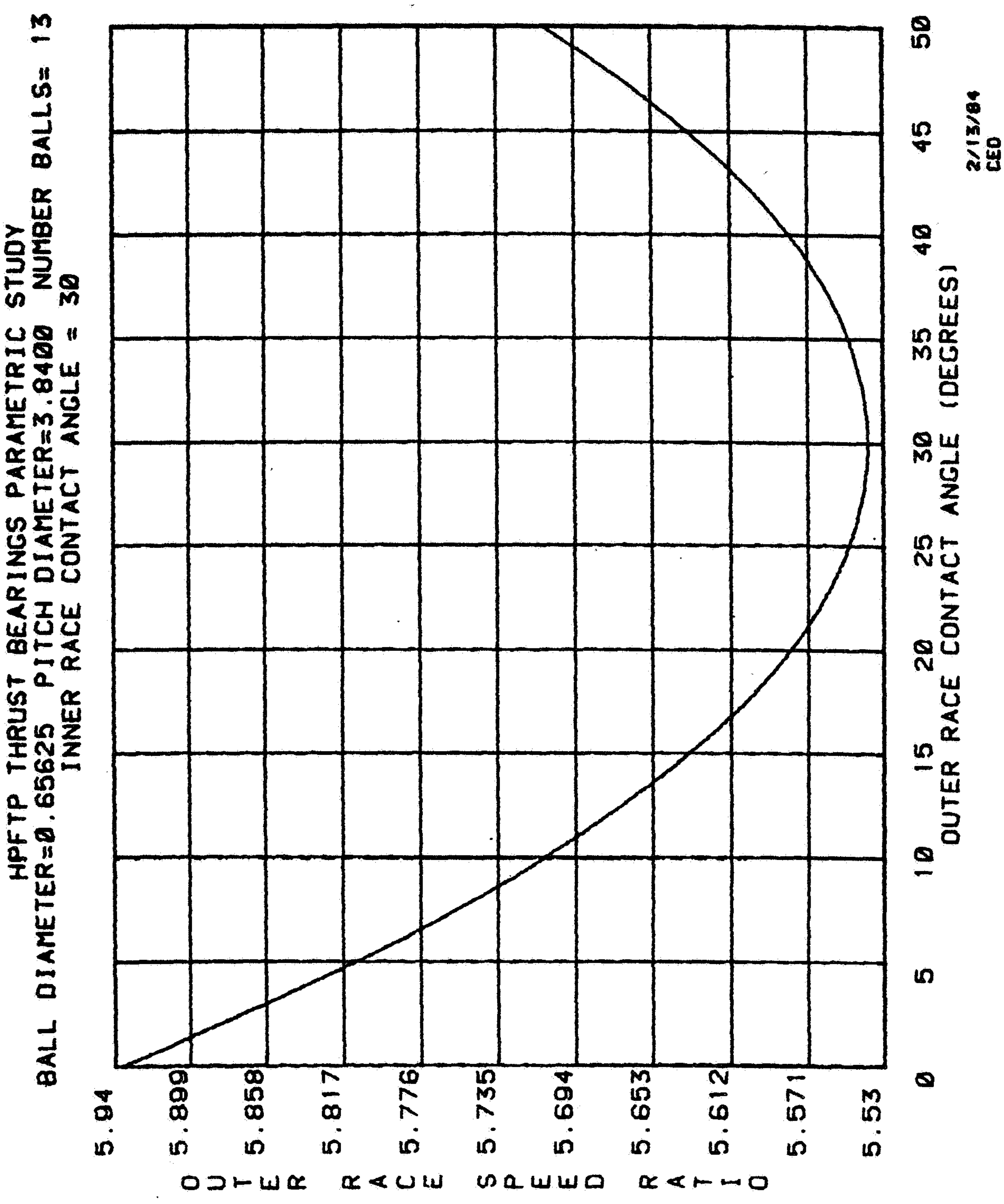

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
OUTER RACE SPEED RATIO
6.41
6.308
6.206
6.104
6.002
5.9
5.798
5.696
5.594
5.492
5.39
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

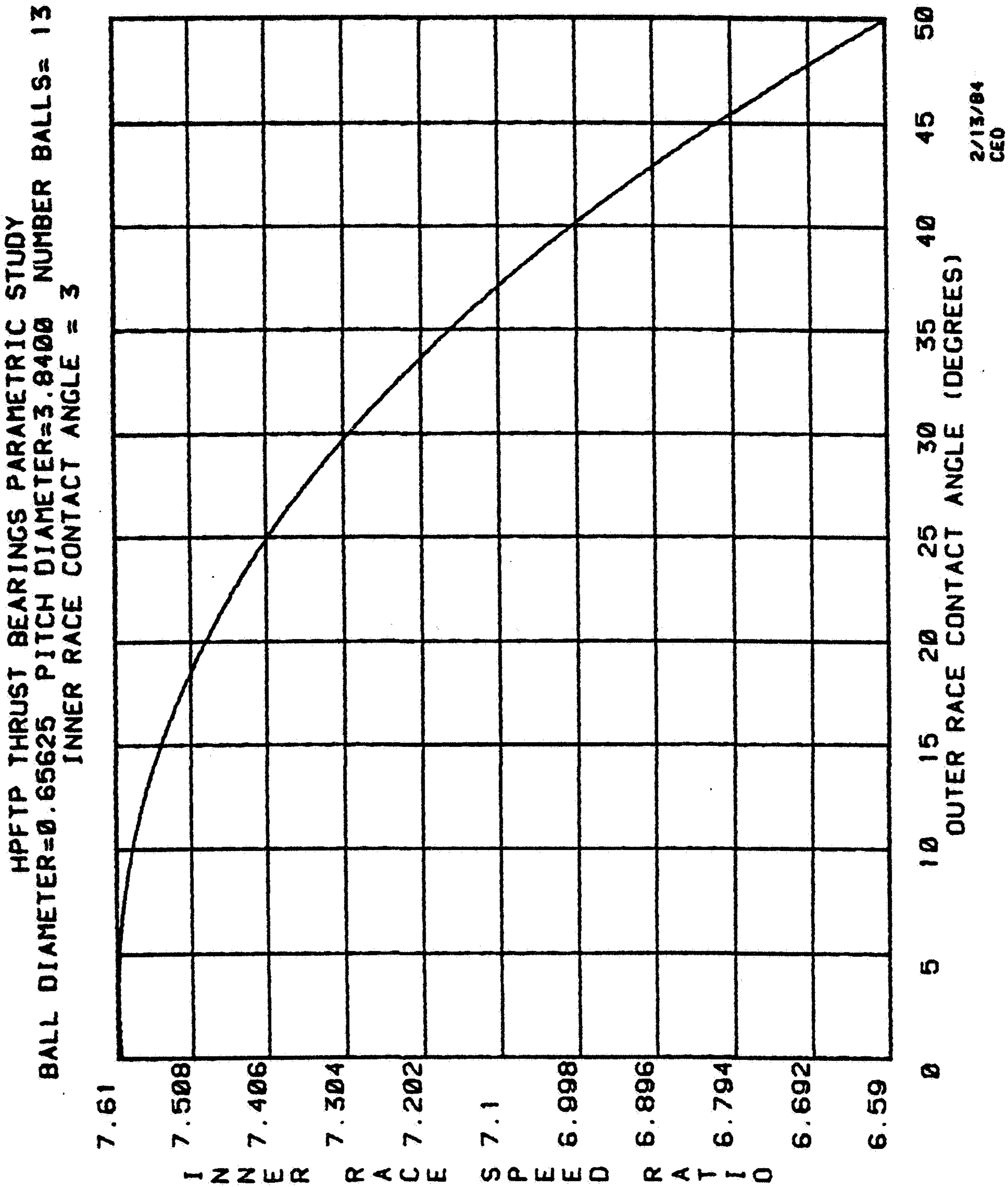
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10

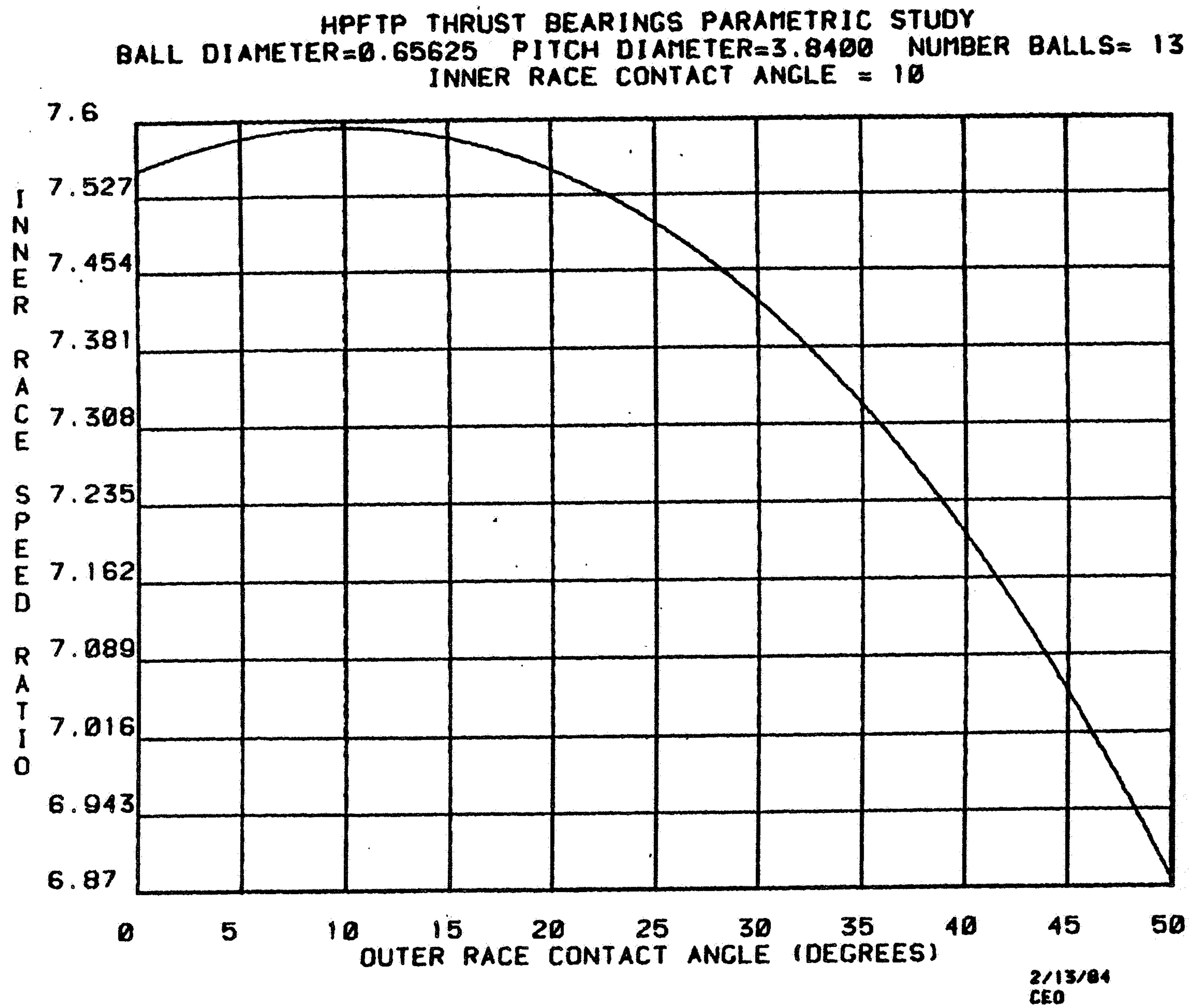


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20

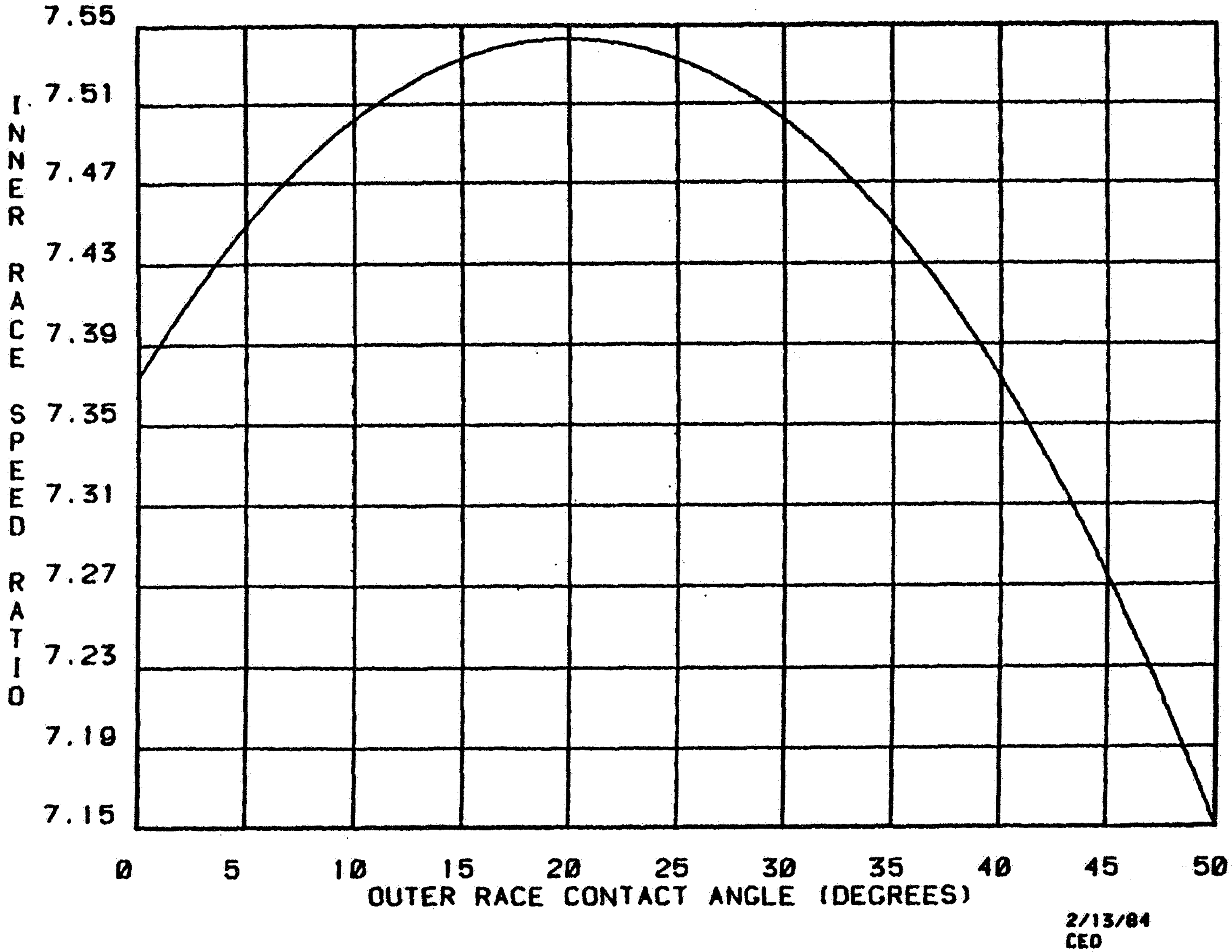


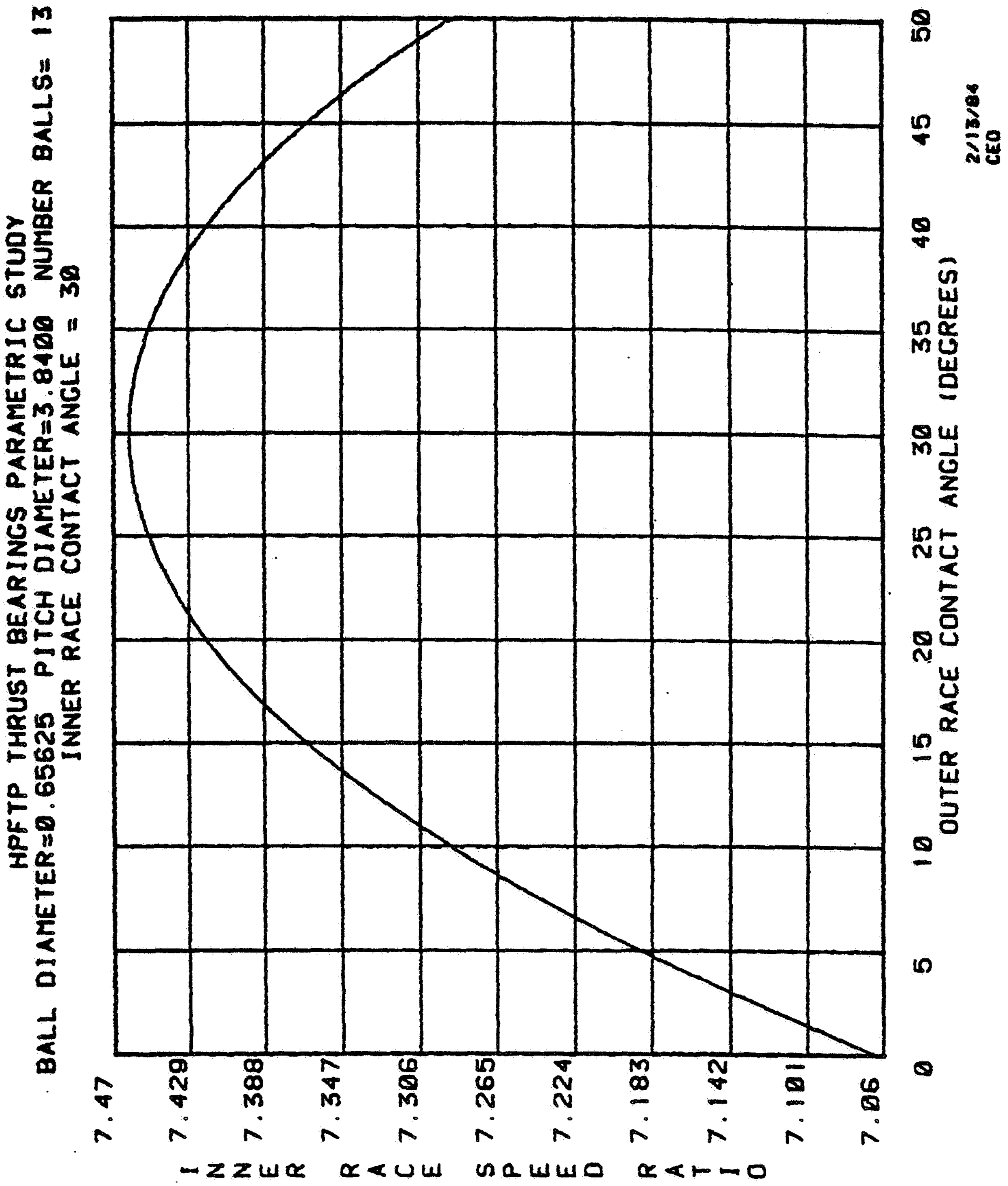

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
OUTER RACE SPEED RATIO
5.94
5.899
5.858
5.817
5.776
5.735
5.694
5.653
5.612
5.571
5.53
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
INNER RACE SPEED RATIO
7.61
7.508
7.406
7.304
7.202
7.1
6.998
6.896
6.794
6.692
6.59
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
INNER RACE SPEED RATIO
7.6
7.527
7.454
7.381
7.308
7.235
7.162
7.089
7.016
6.943
6.87
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20



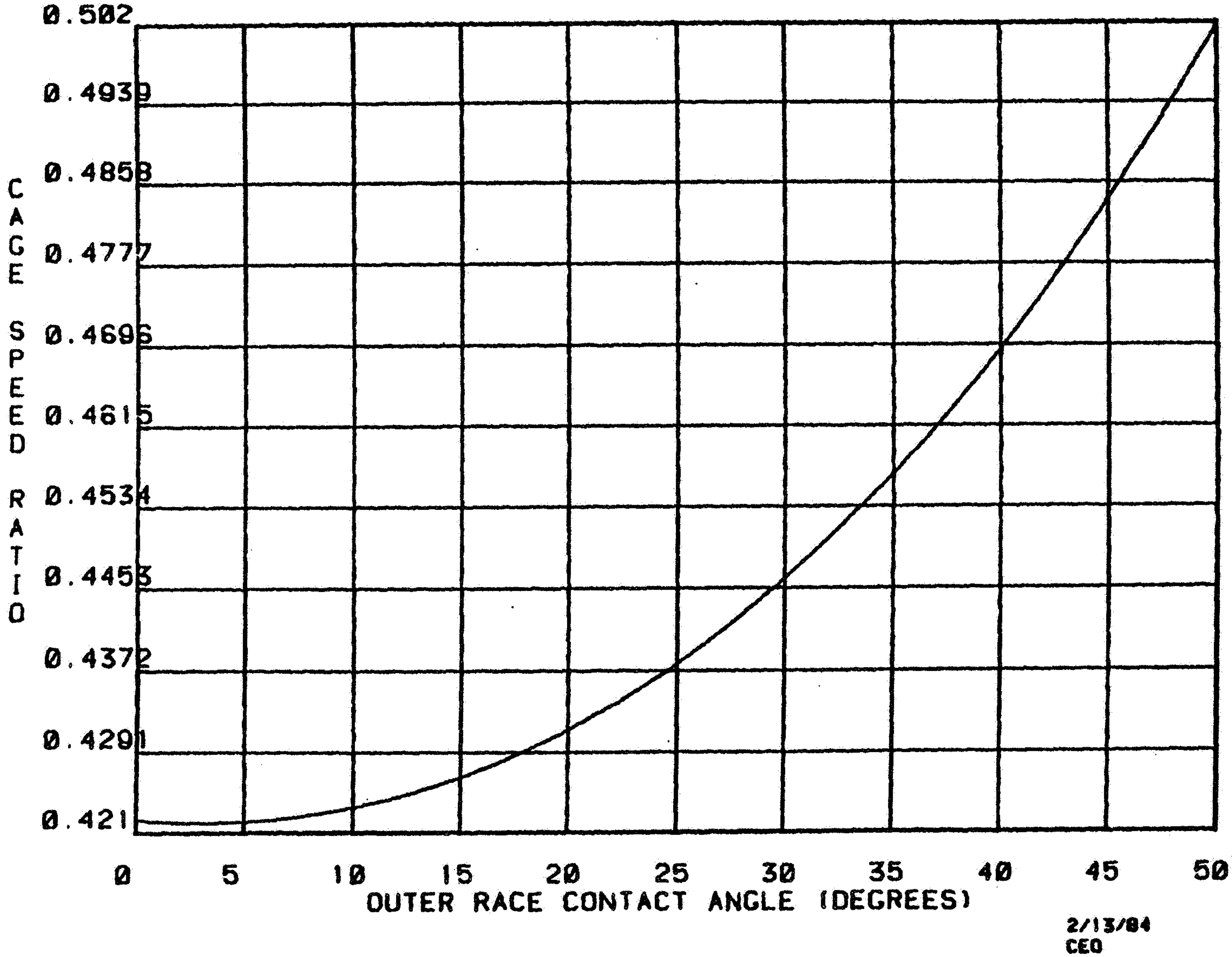


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
INNER RACE SPEED RATIO
7.47
7.429
7.388
7.347
7.306
7.265
7.224
7.183
7.142
7.101
7.06
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

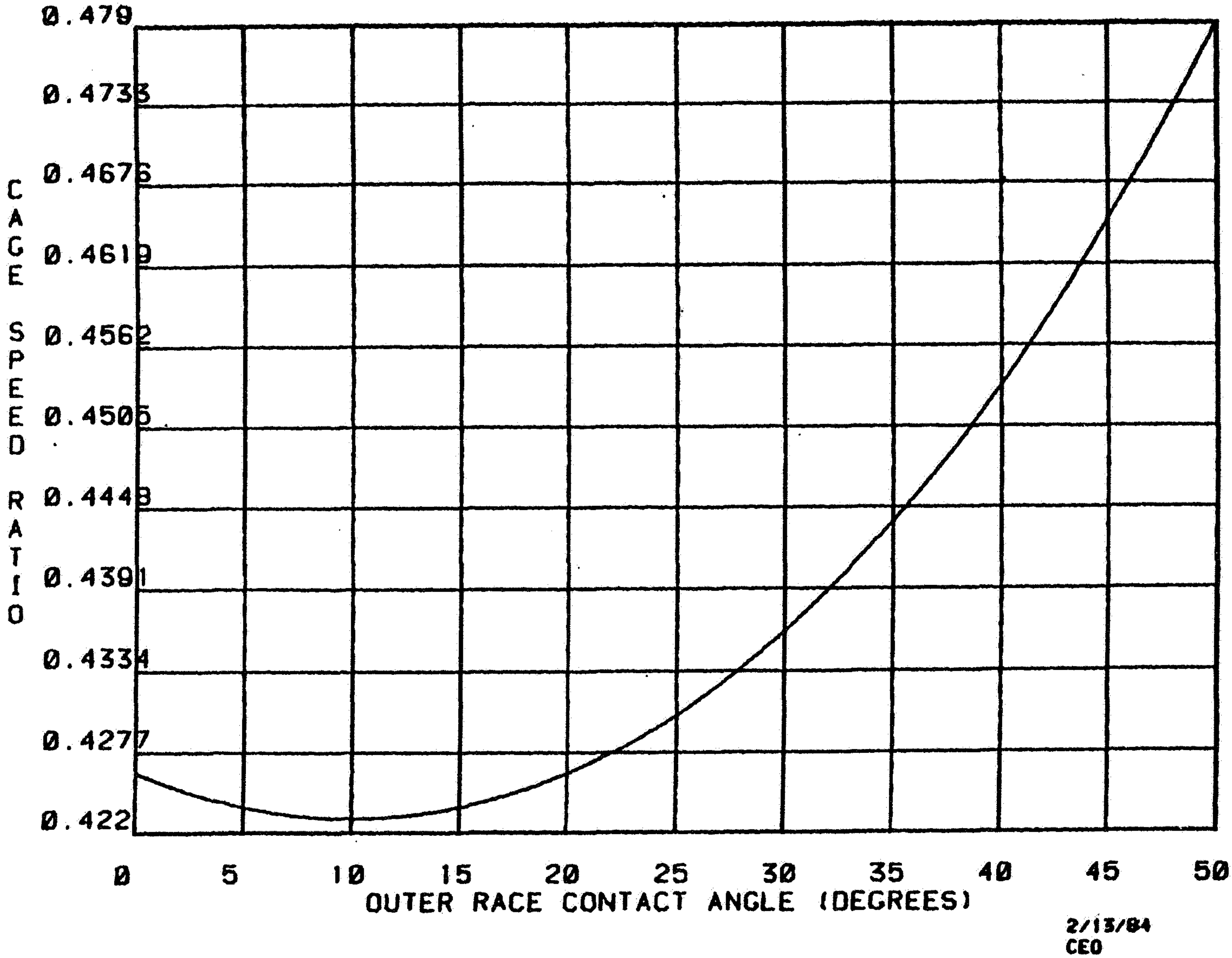
SPEED RATIO OF
HPOTP TURBINE BEARINGS
3-, 10-, 20-, AND 30-DEGREE α_i
(Inner Race Contact Angle)

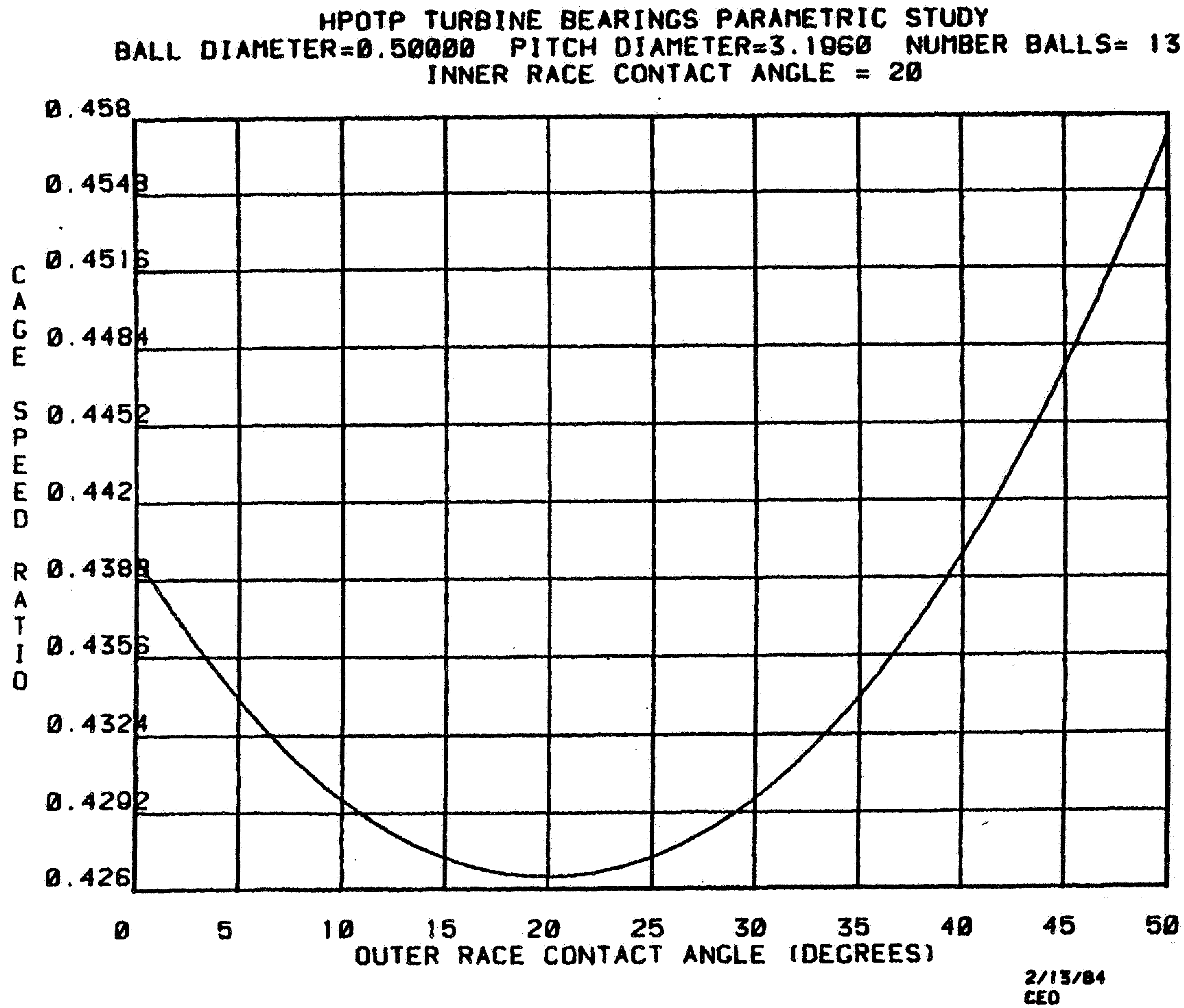
Ball Diameter = 0.50 inch
Pitch Diameter = 3.196 inches
Number of Balls = 13

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3

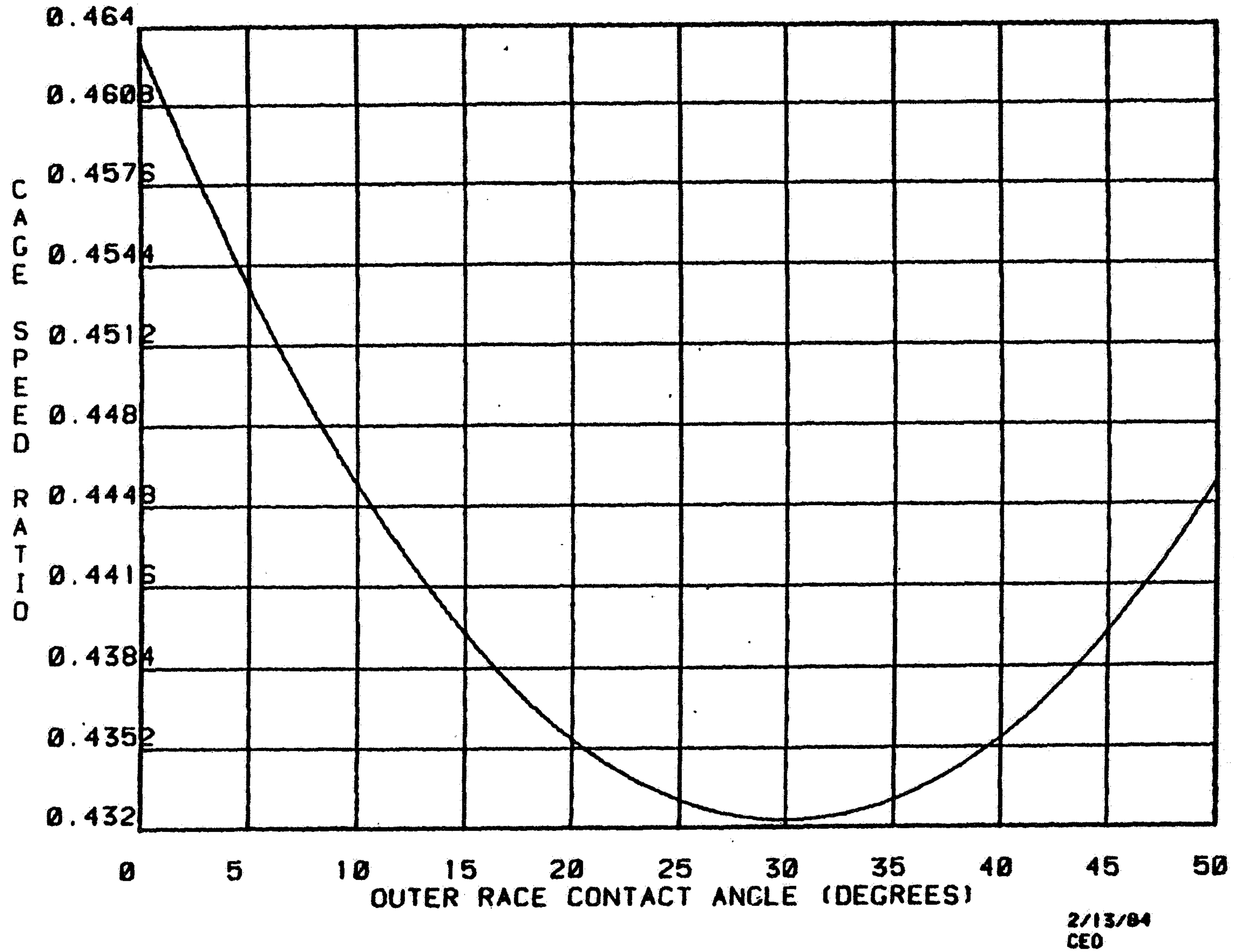


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10

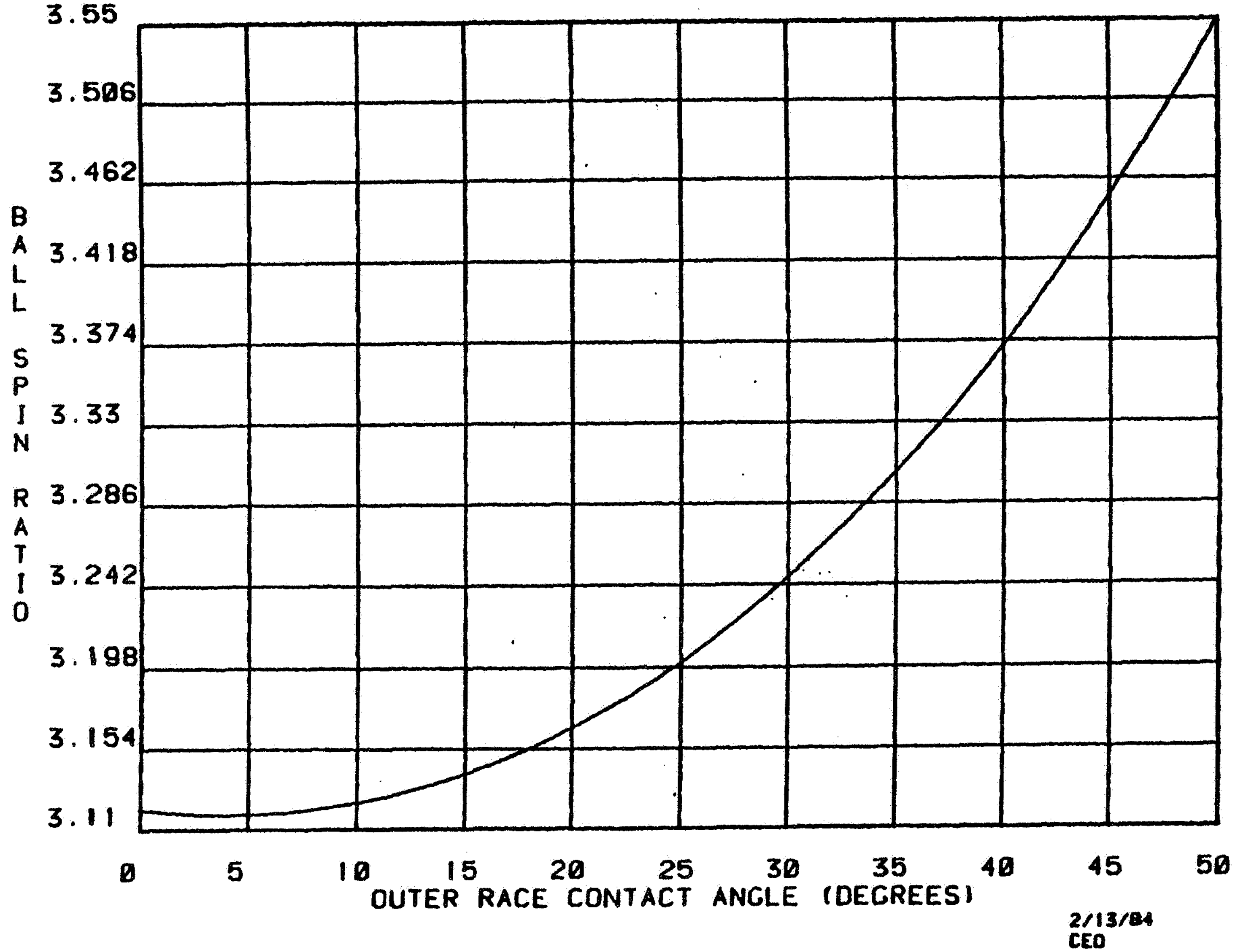


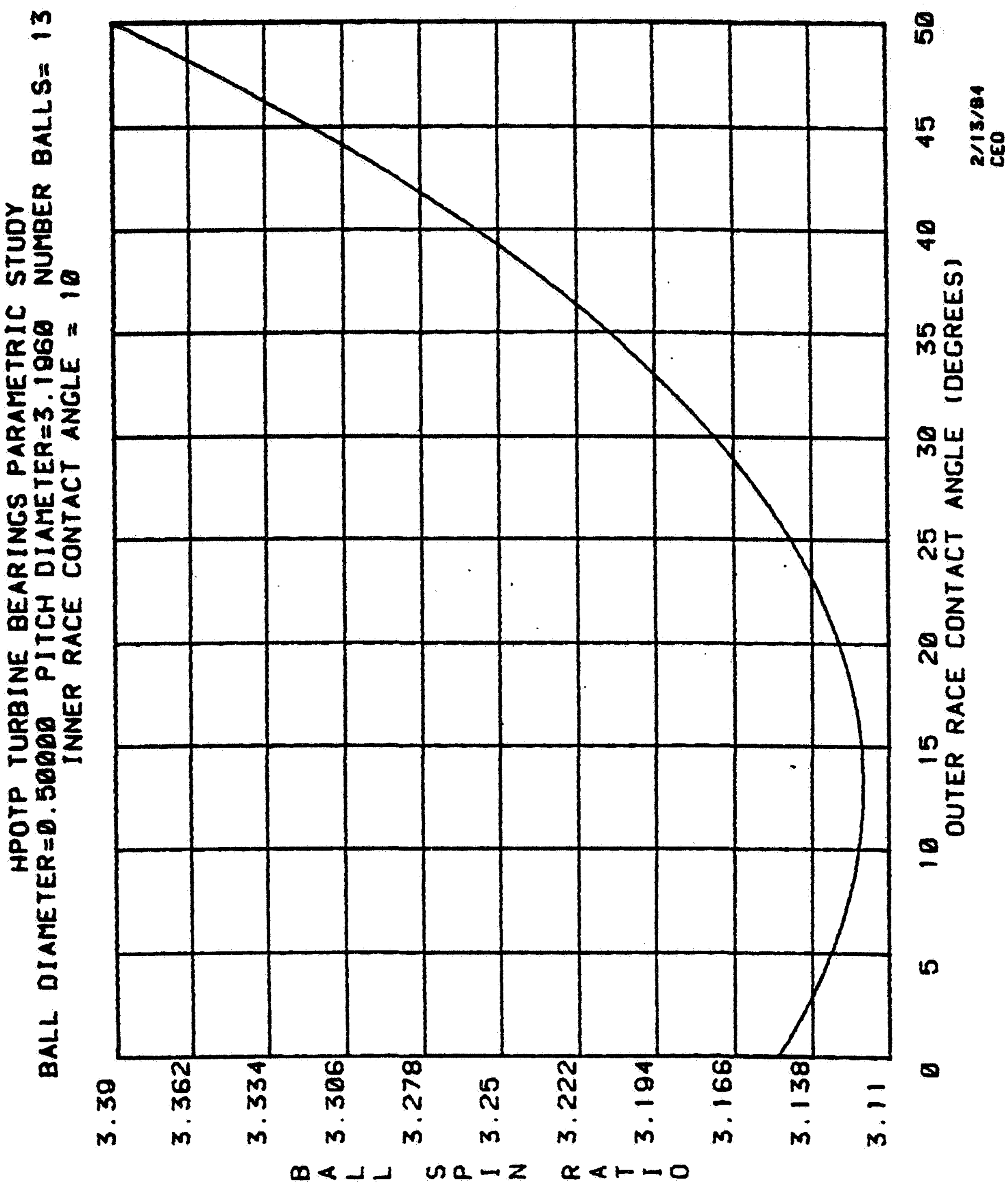

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
0.458
0.4548
0.4516
0.4484
0.4452
0.442
0.4388
0.4356
0.4324
0.4292
0.426
CAGE SPEED RATIO
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30

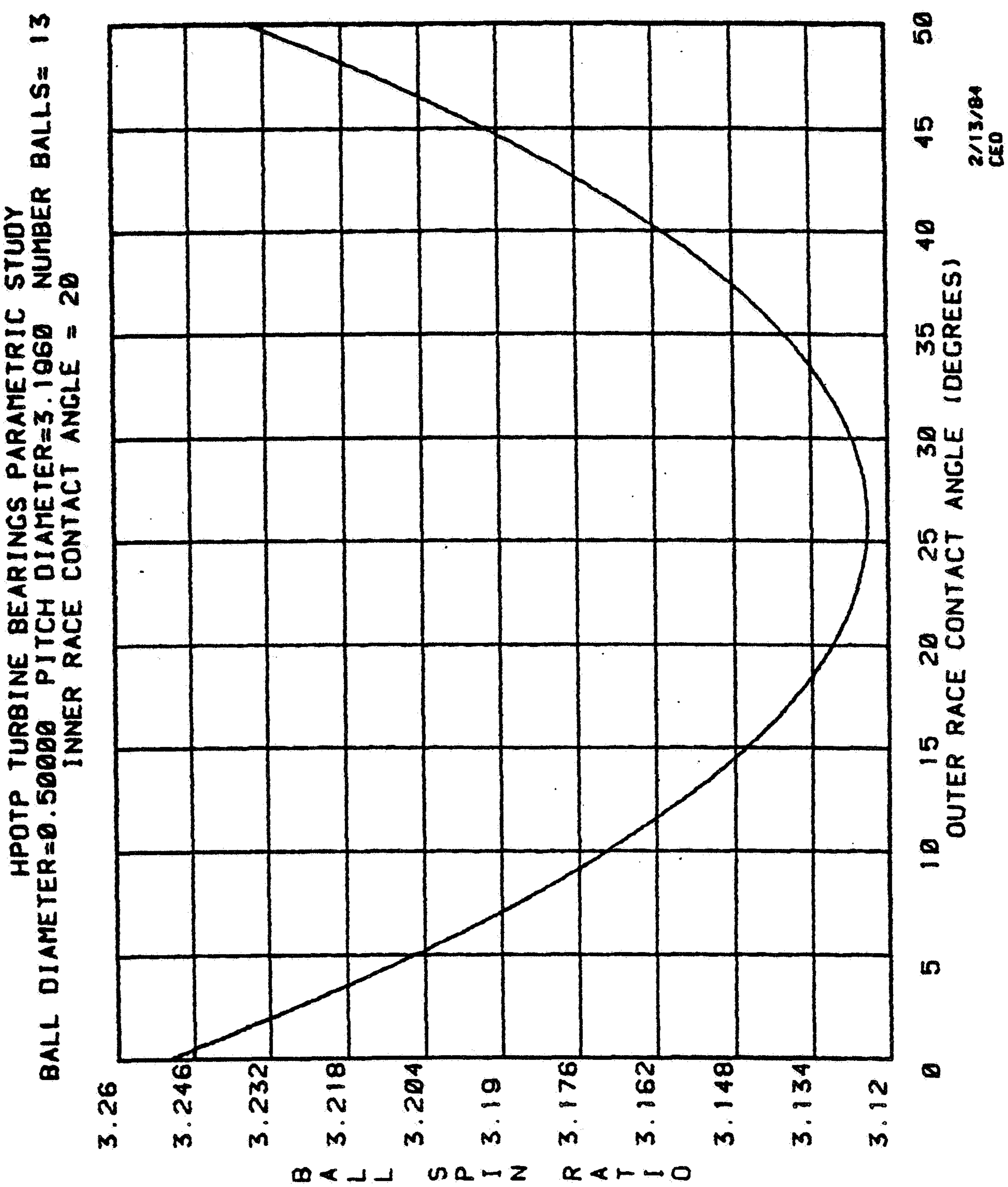


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3



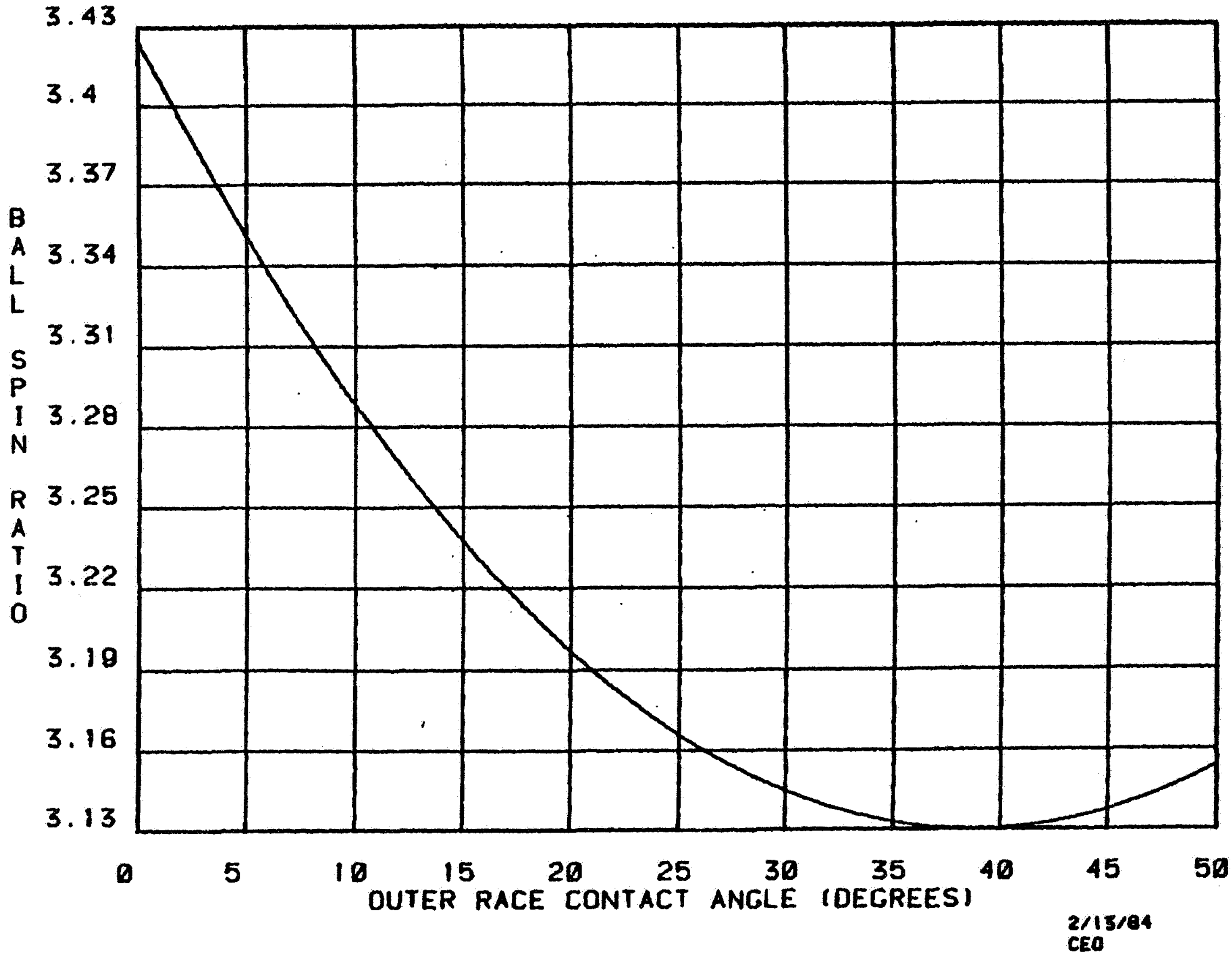


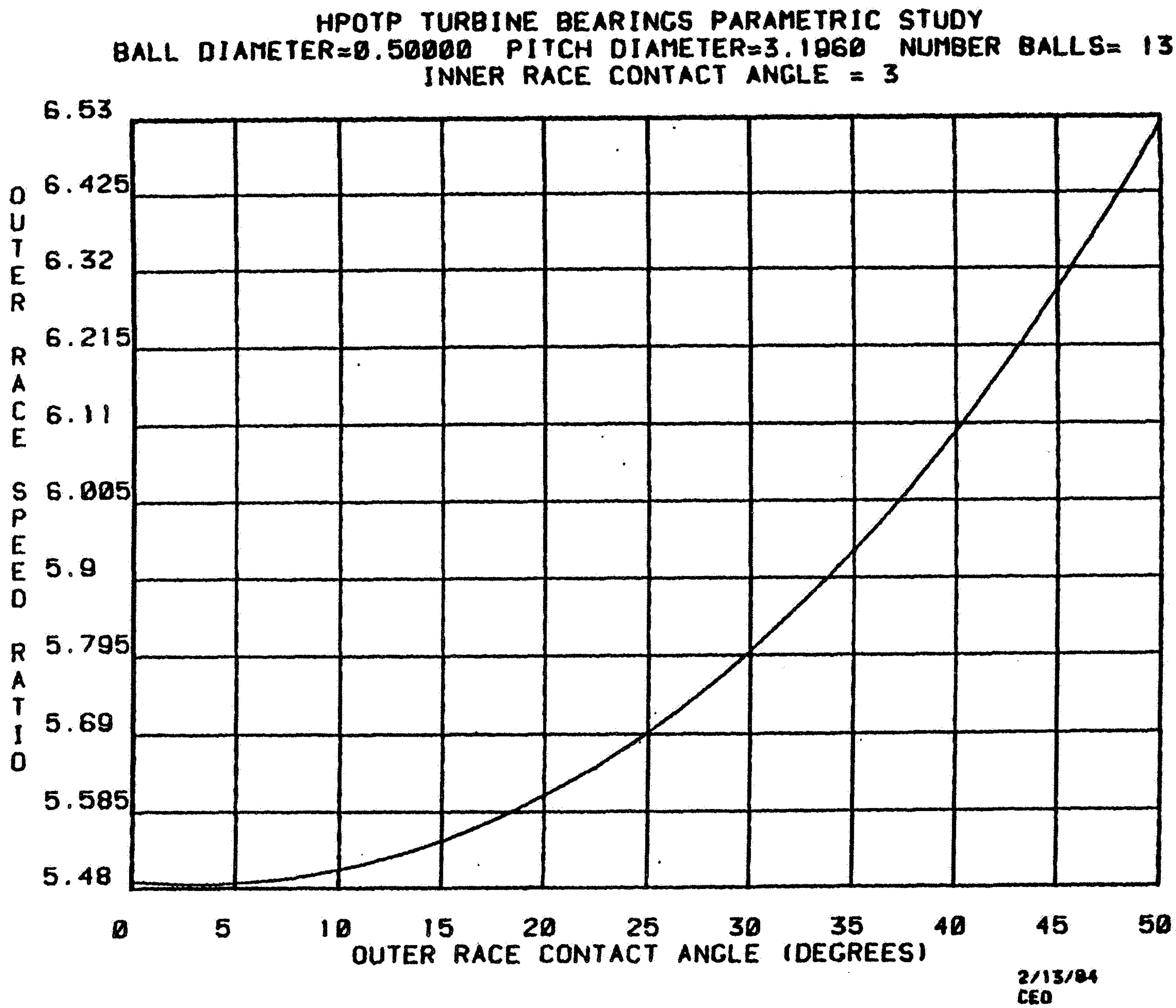
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.19600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
BALL SPIN RATIO
3.39
3.362
3.334
3.306
3.278
3.25
3.222
3.194
3.166
3.138
3.11
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

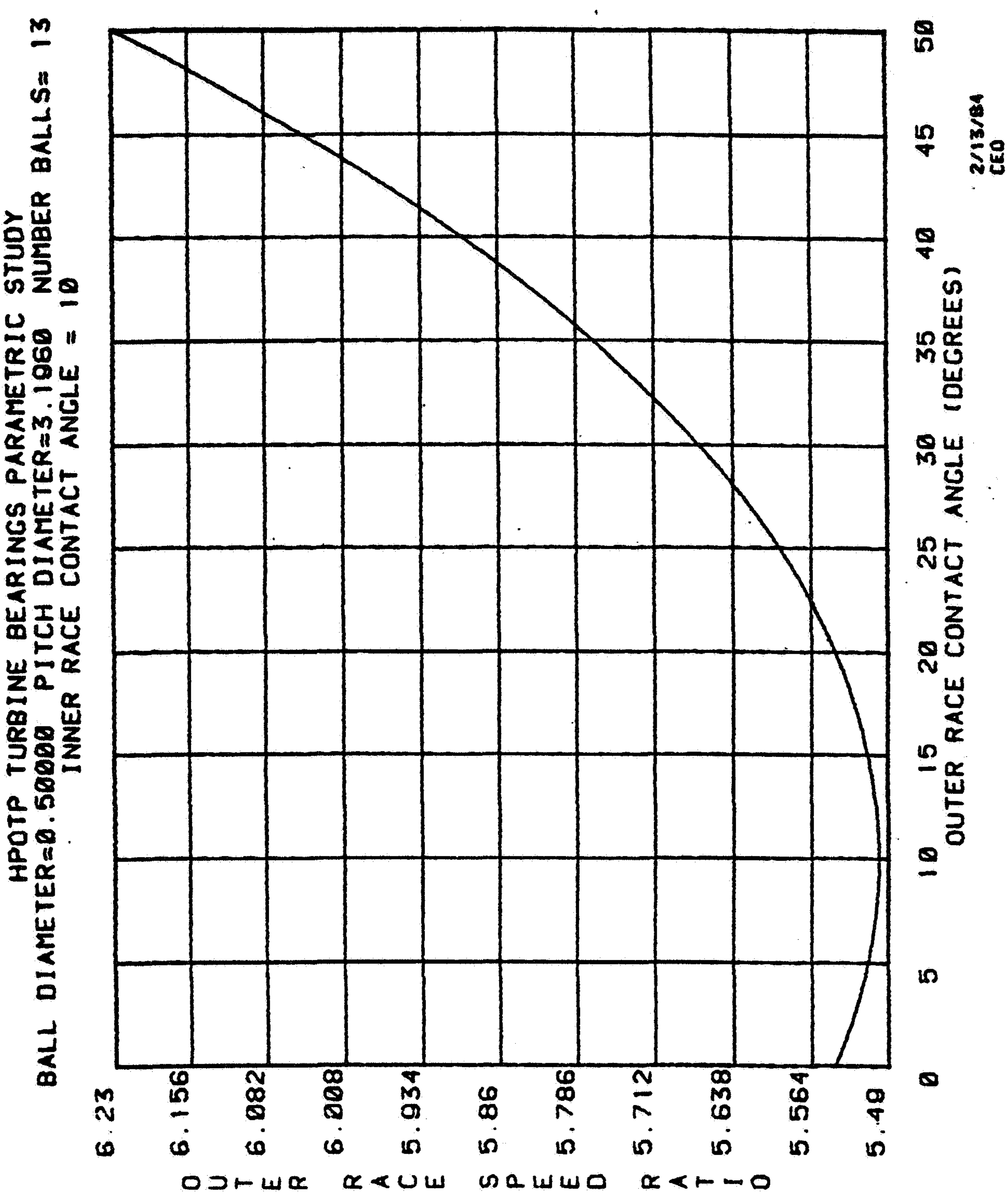


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
BALL SPIN RATIO
3.26
3.246
3.232
3.218
3.204
3.19
3.176
3.162
3.148
3.134
3.12
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

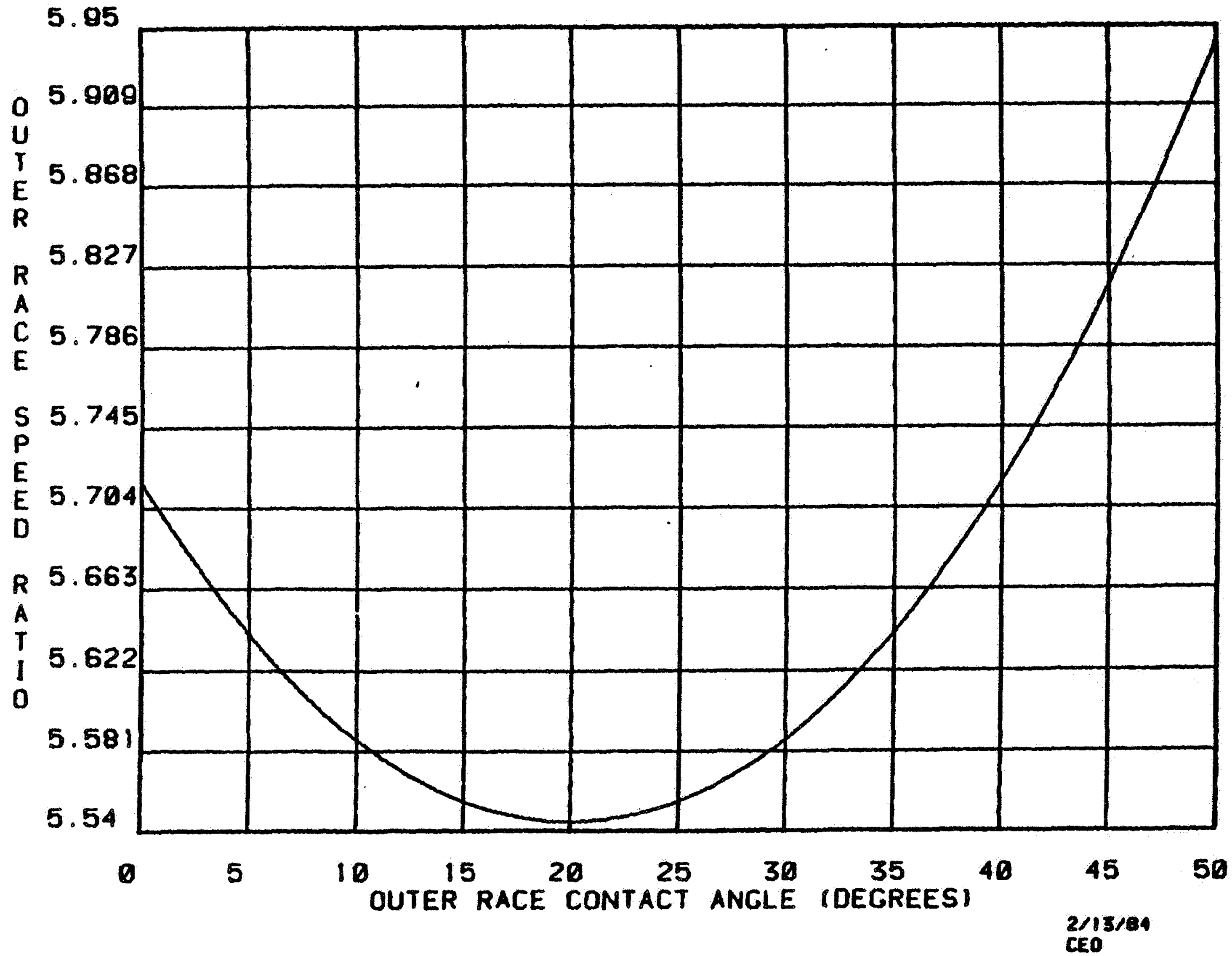
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30



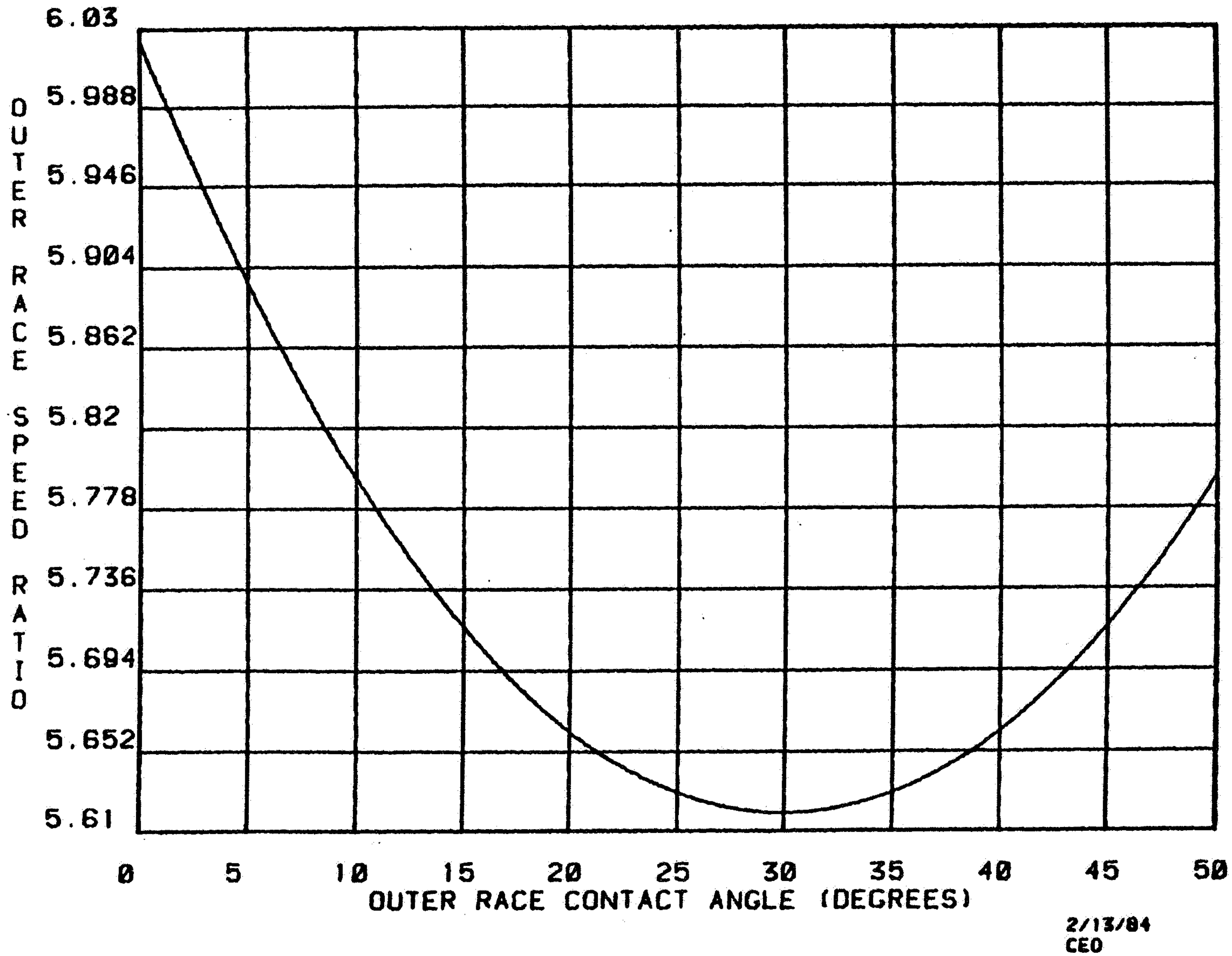

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
OUTER RACE SPEED RATIO
6.53
6.425
6.32
6.215
6.11
6.005
5.9
5.795
5.69
5.585
5.48
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

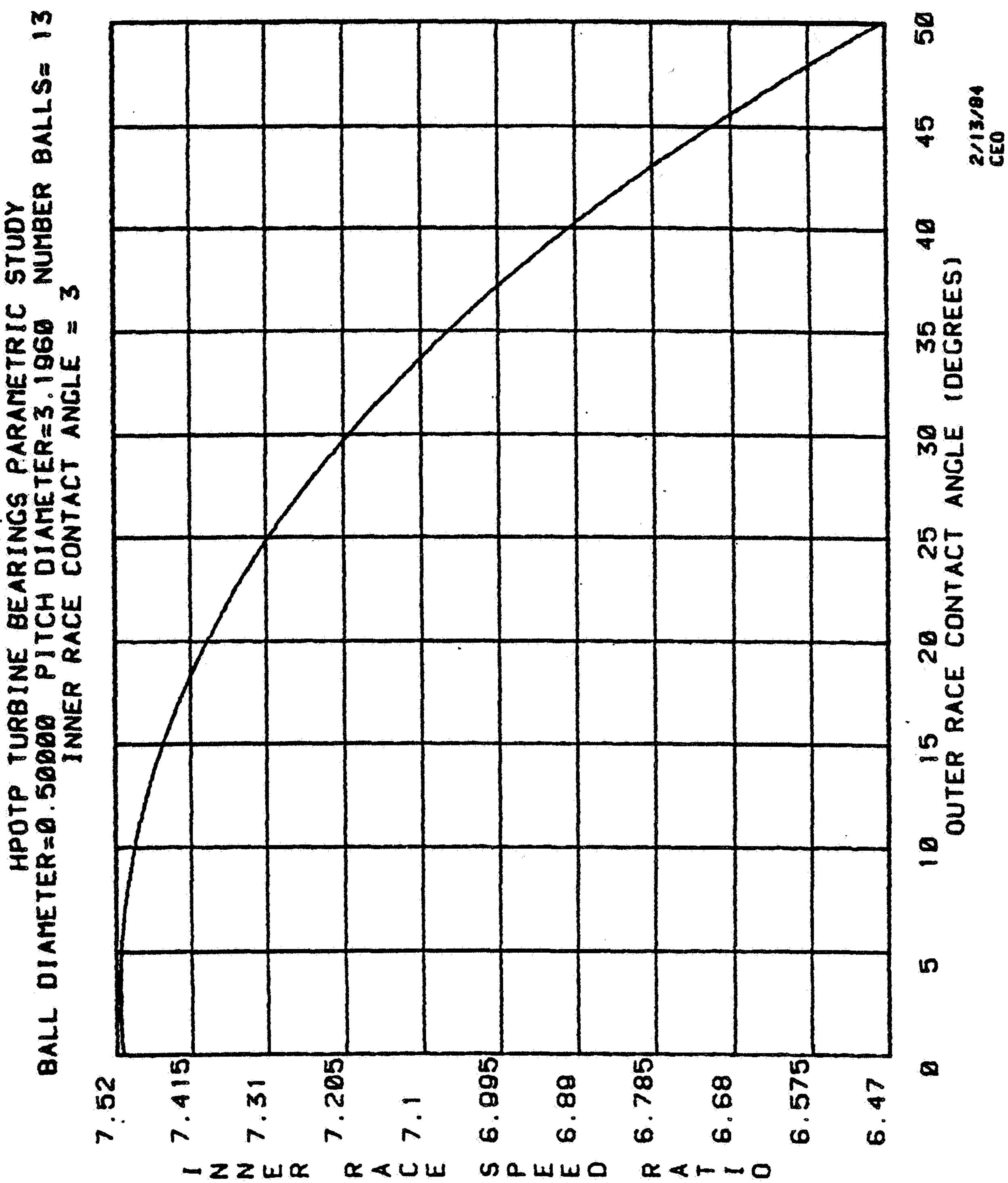

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
OUTER RACE SPEED RATIO
6.23
6.156
6.082
6.008
5.934
5.86
5.786
5.712
5.638
5.564
5.49
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20



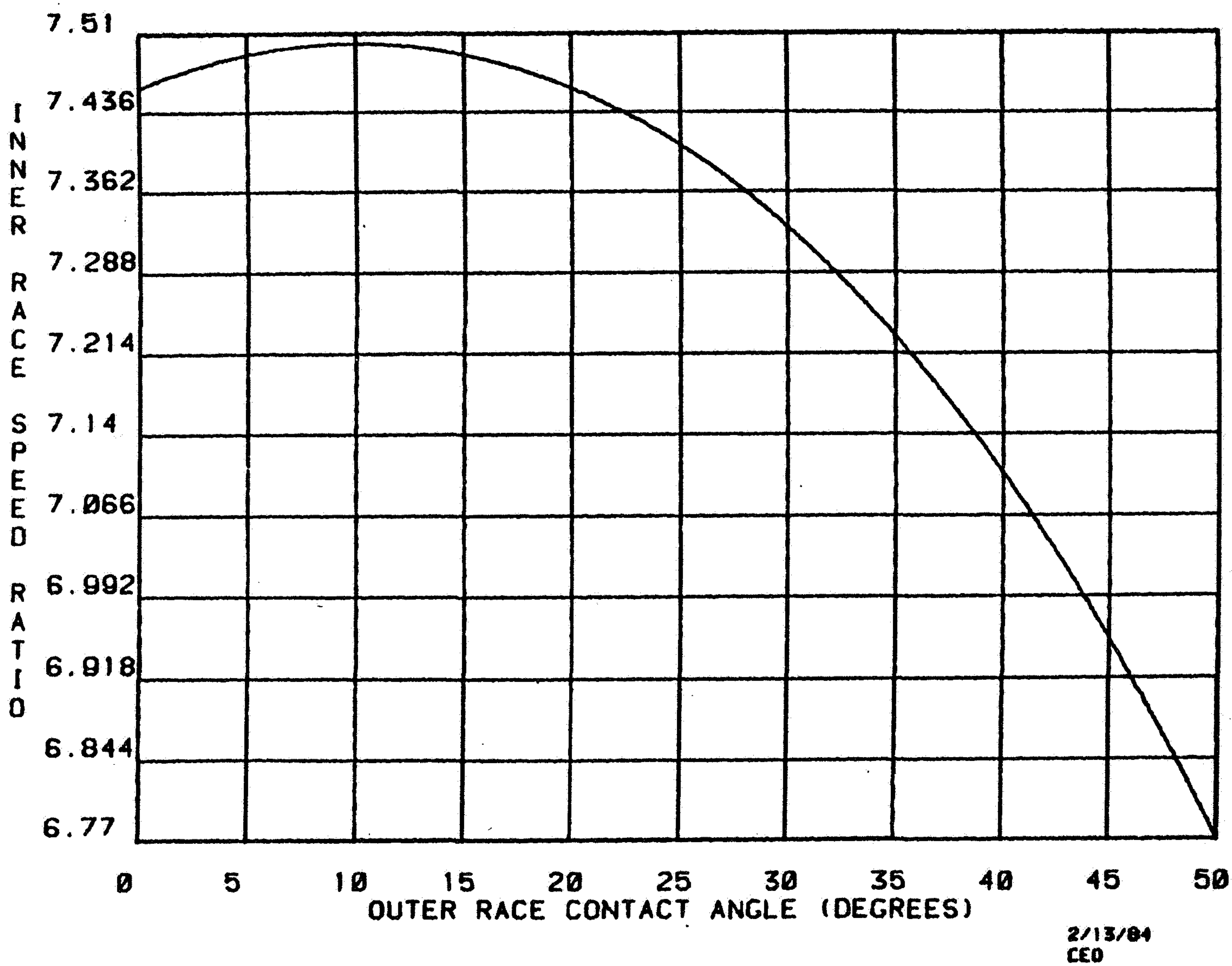
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30

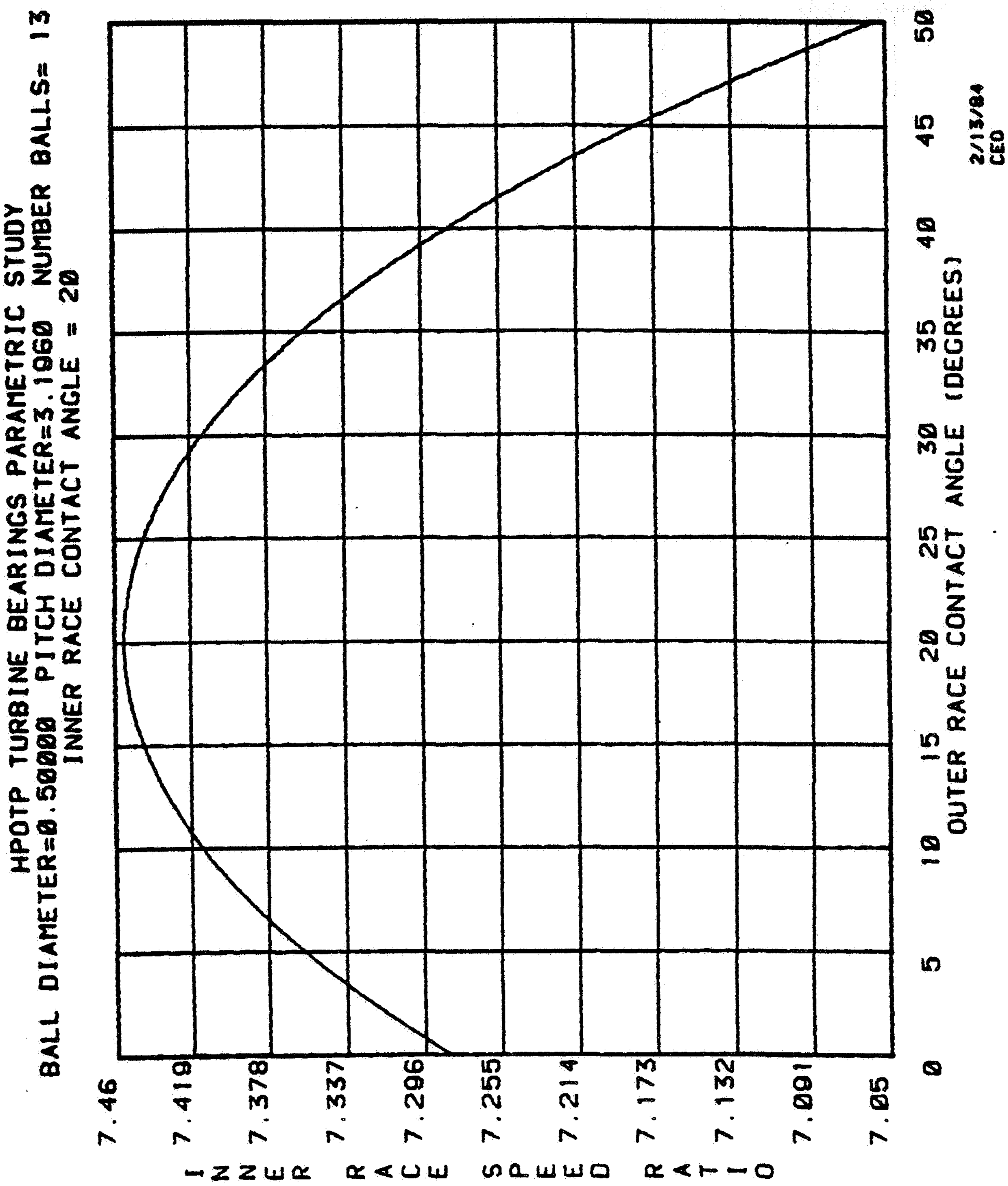


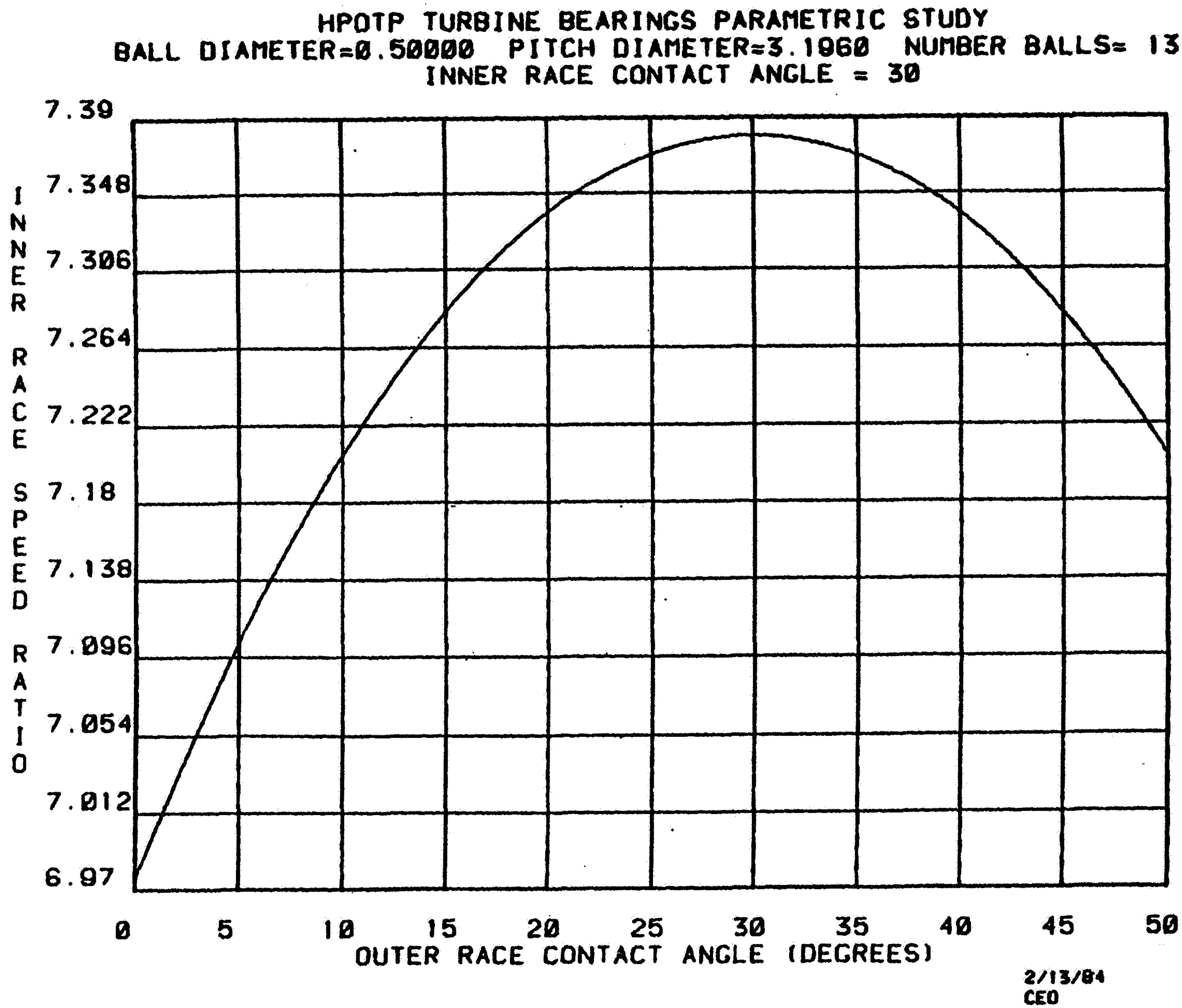


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
INNER RACE SPEED RATIO
7.52
7.415
7.31
7.205
7.1
6.995
6.89
6.785
6.68
6.575
6.47
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10

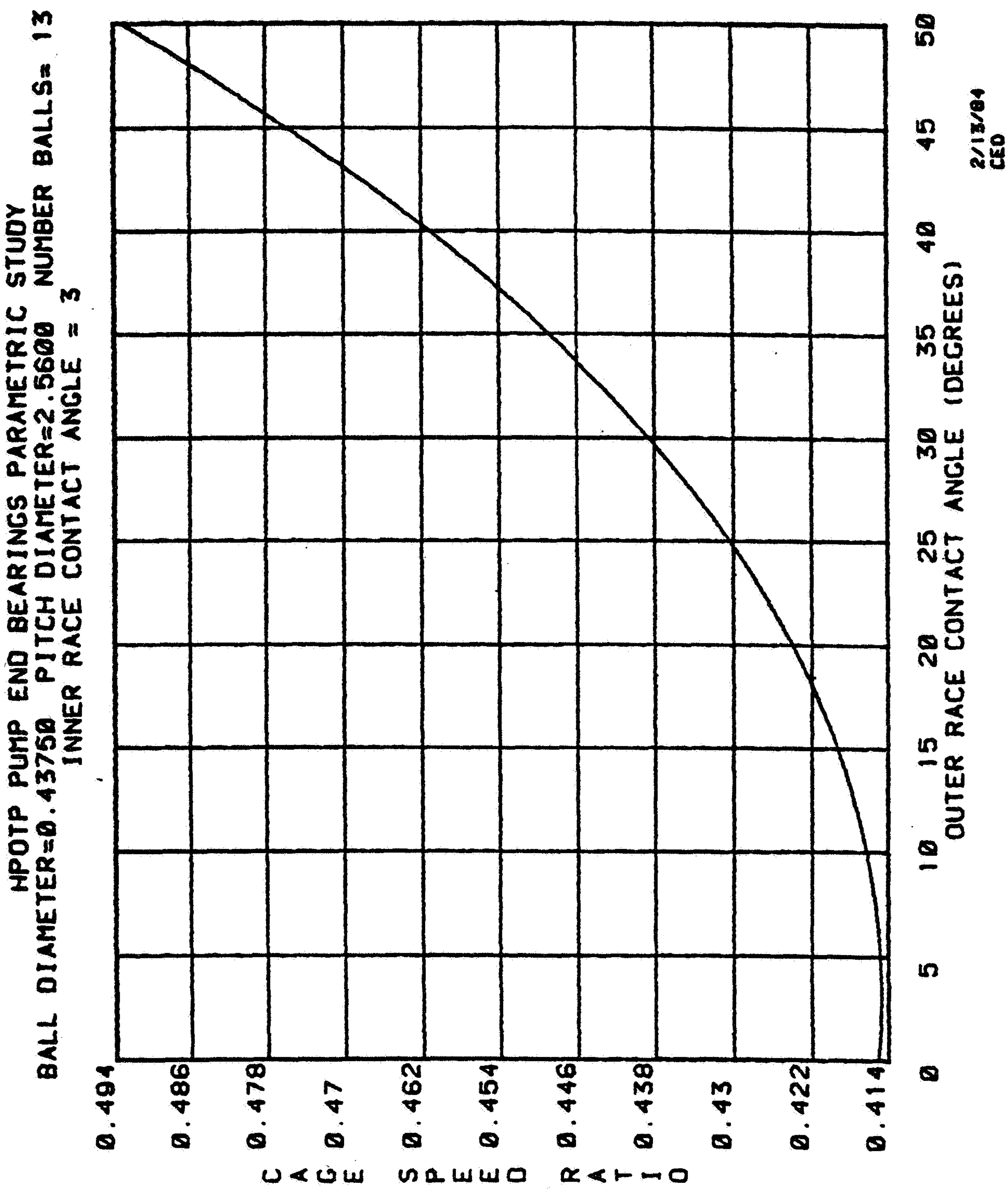



HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
INNER RACE SPEED RATIO
7.46
7.419
7.378
7.337
7.296
7.255
7.214
7.173
7.132
7.091
7.05
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

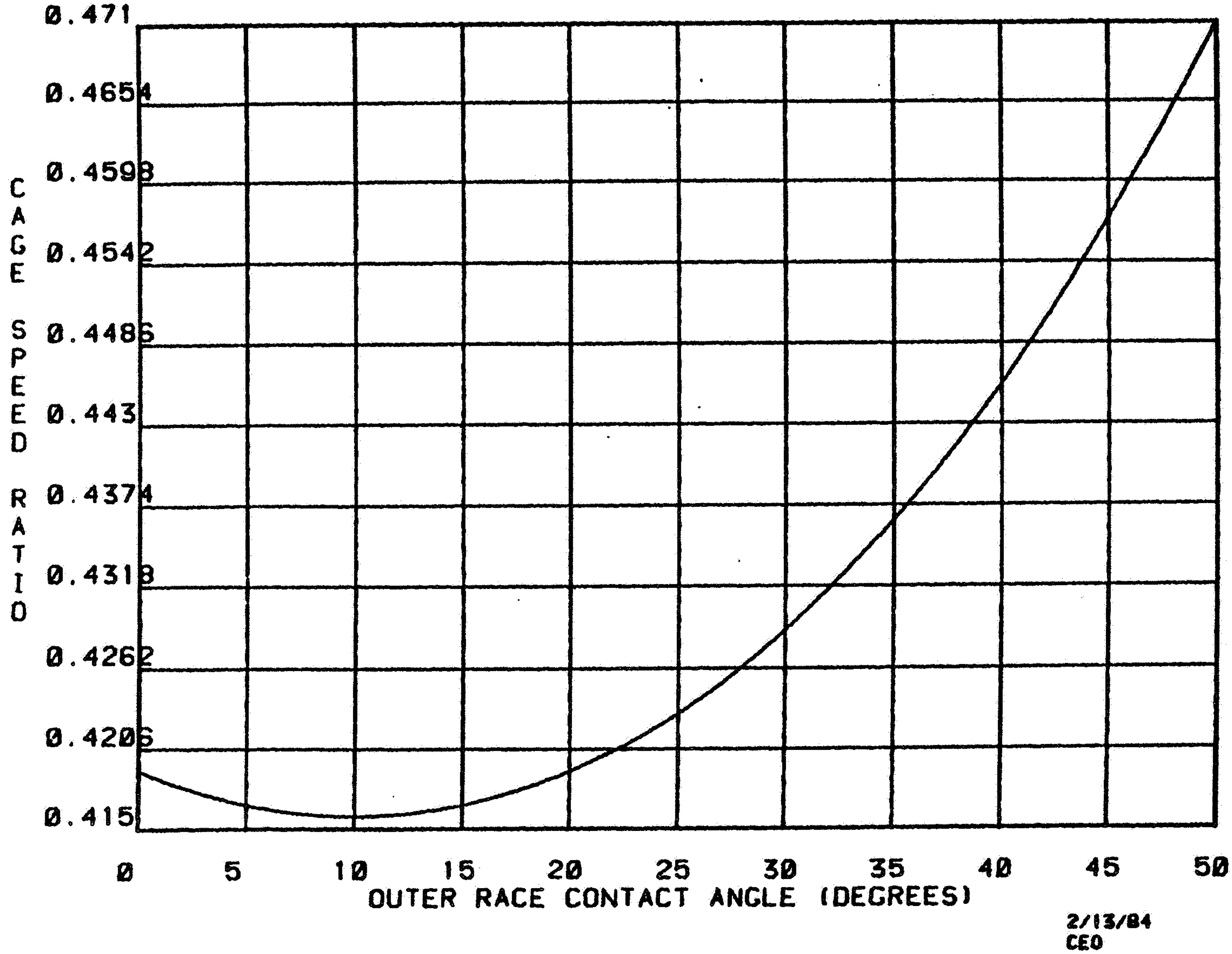

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
7.39
7.348
7.306
7.264
7.222
7.18
7.138
7.096
7.054
7.012
6.97
INNER RACE SPEED RATIO
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

SPEED RATIO OF
HPOTP PUMP END BEARINGS
3-, 10-, 20-, AND 30-DEGREE α_i
(Inner Race Contact Angle)

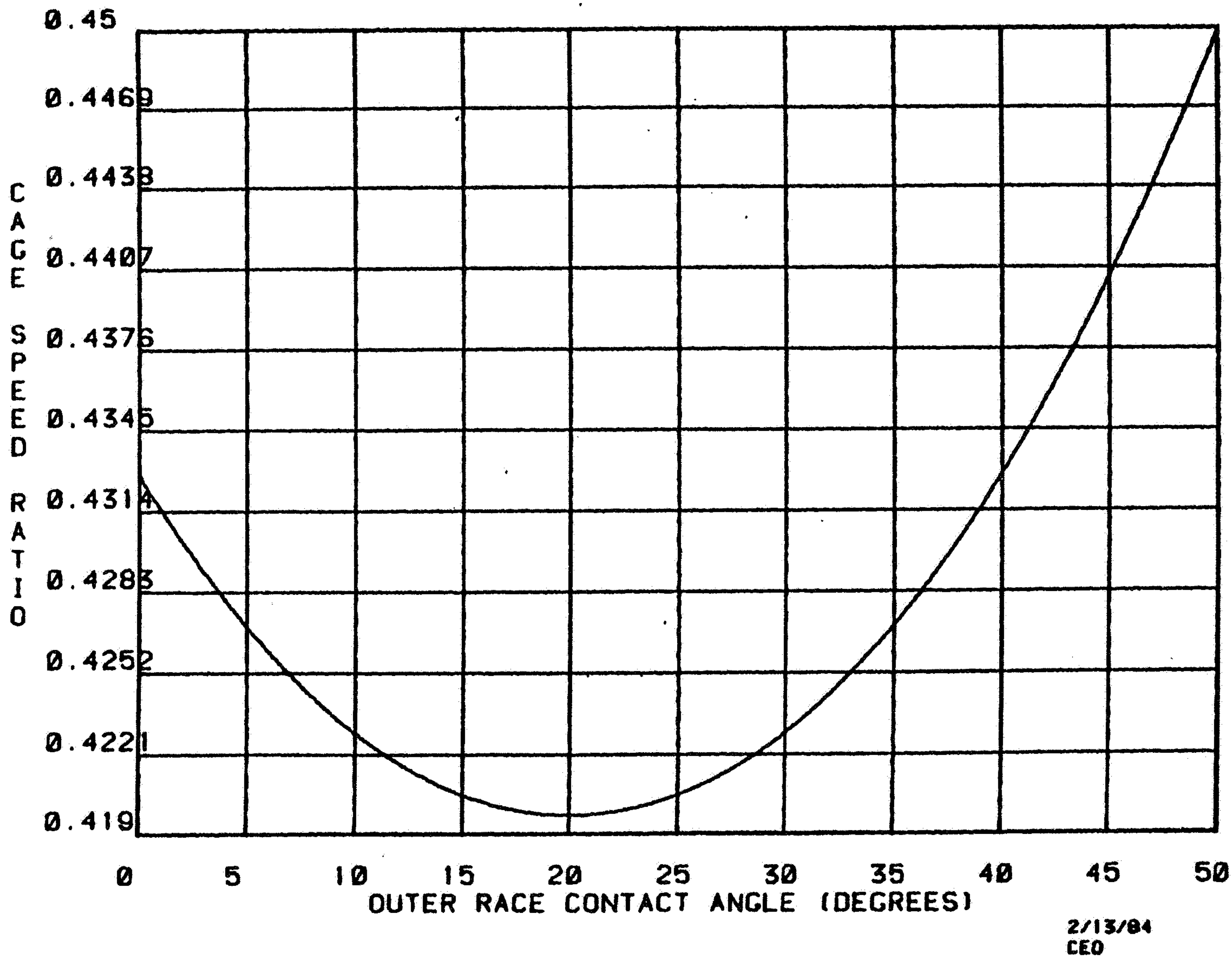
Ball Diameter = 0.4375 inch
Pitch Diameter = 2.56 inches
Number of Balls = 13

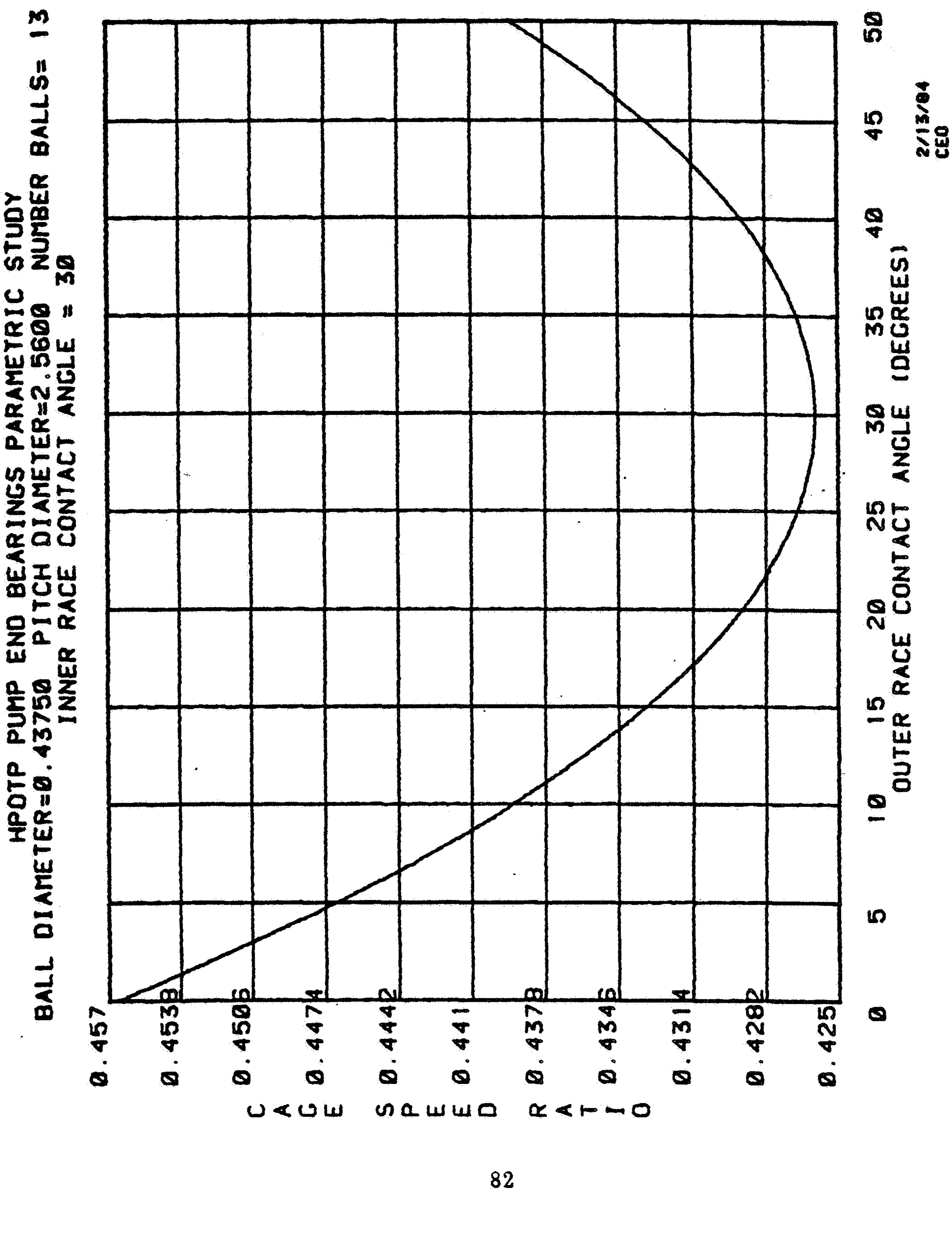

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
CAGE SPEED RATIO
0.494
0.486
0.478
0.47
0.462
0.454
0.446
0.438
0.43
0.422
0.414
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

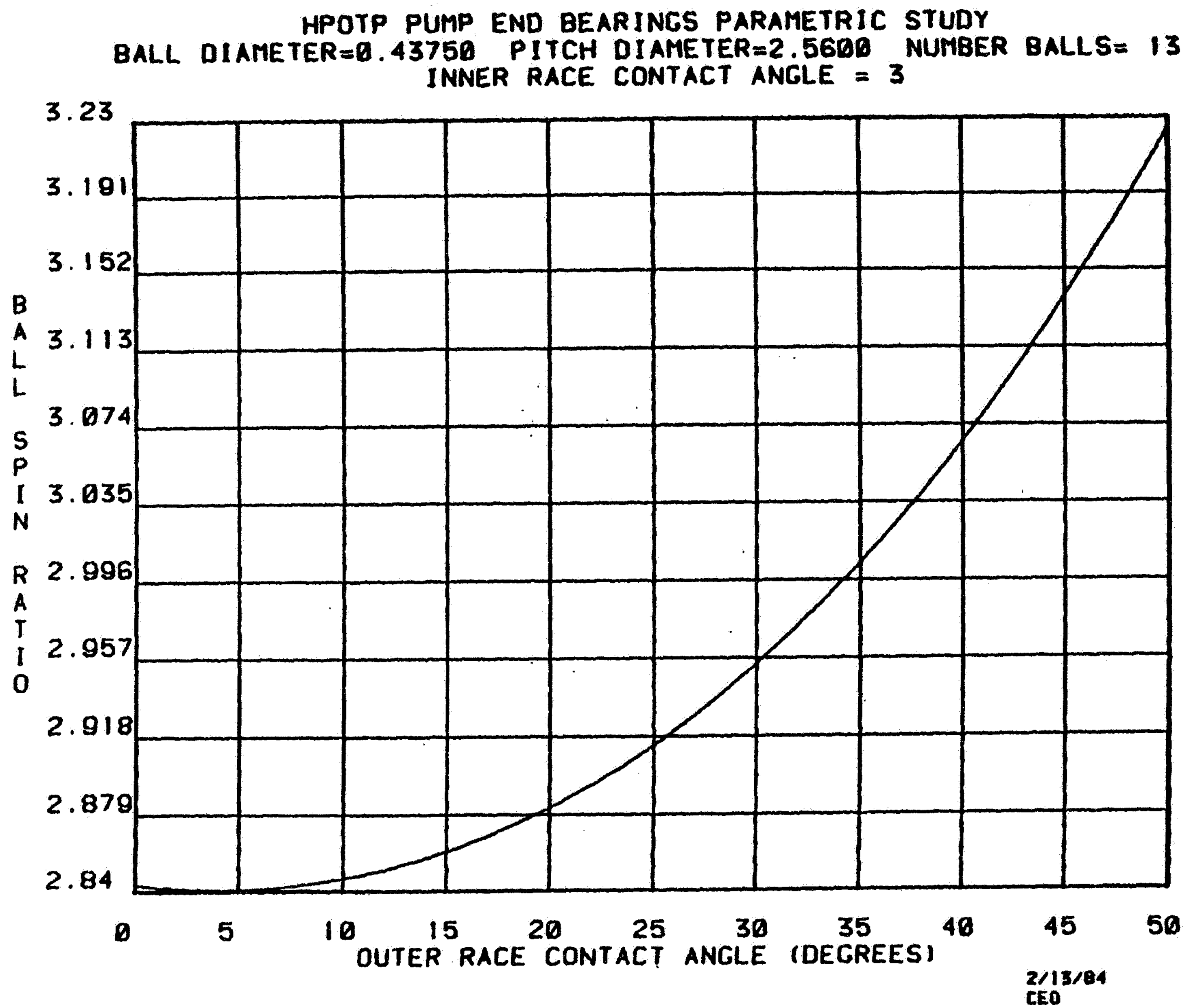
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10



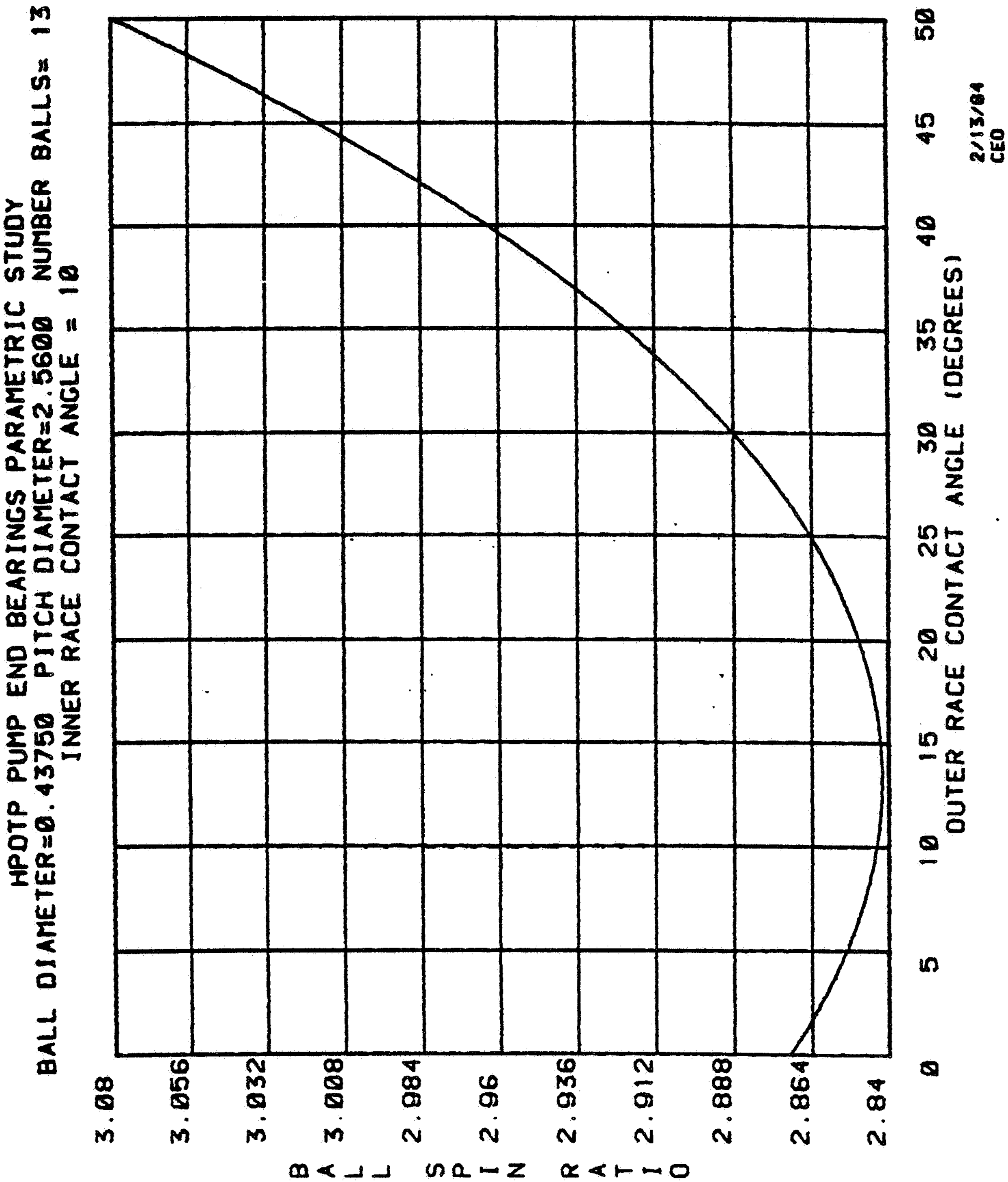
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20

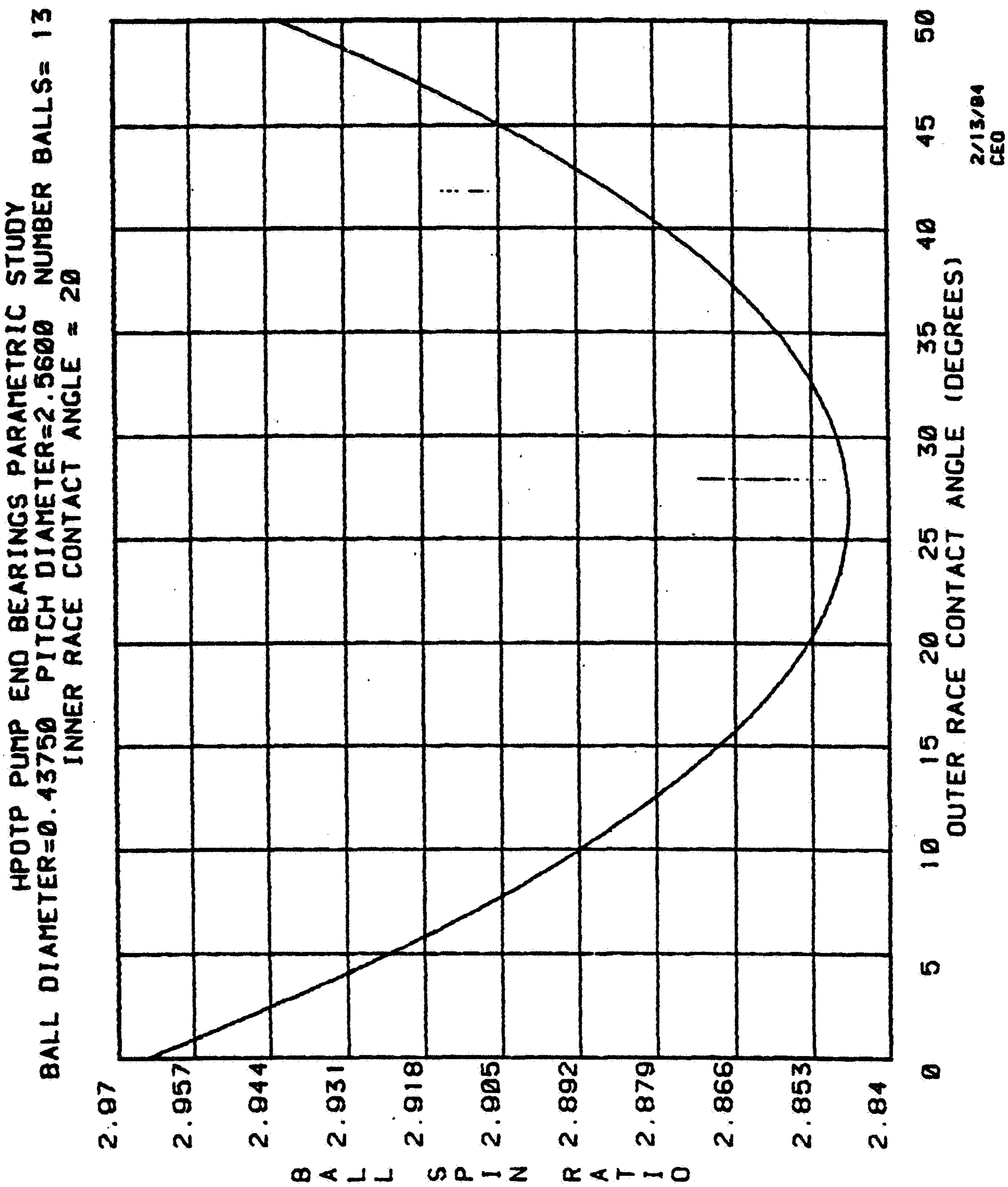


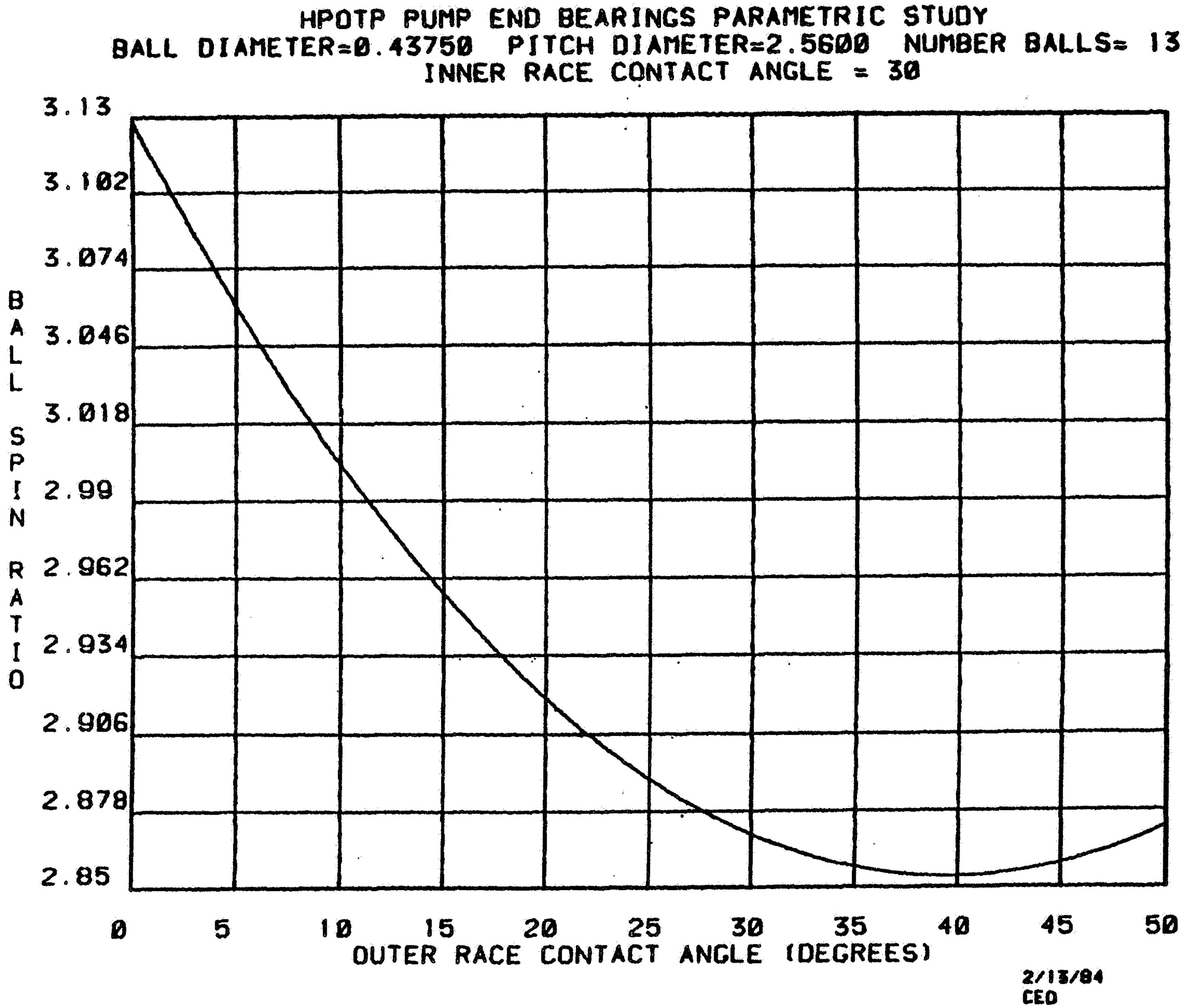

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
CAGE SPEED RATIO
0.457
0.4538
0.4506
0.4474
0.4442
0.441
0.4378
0.4346
0.4314
0.4282
0.425
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO



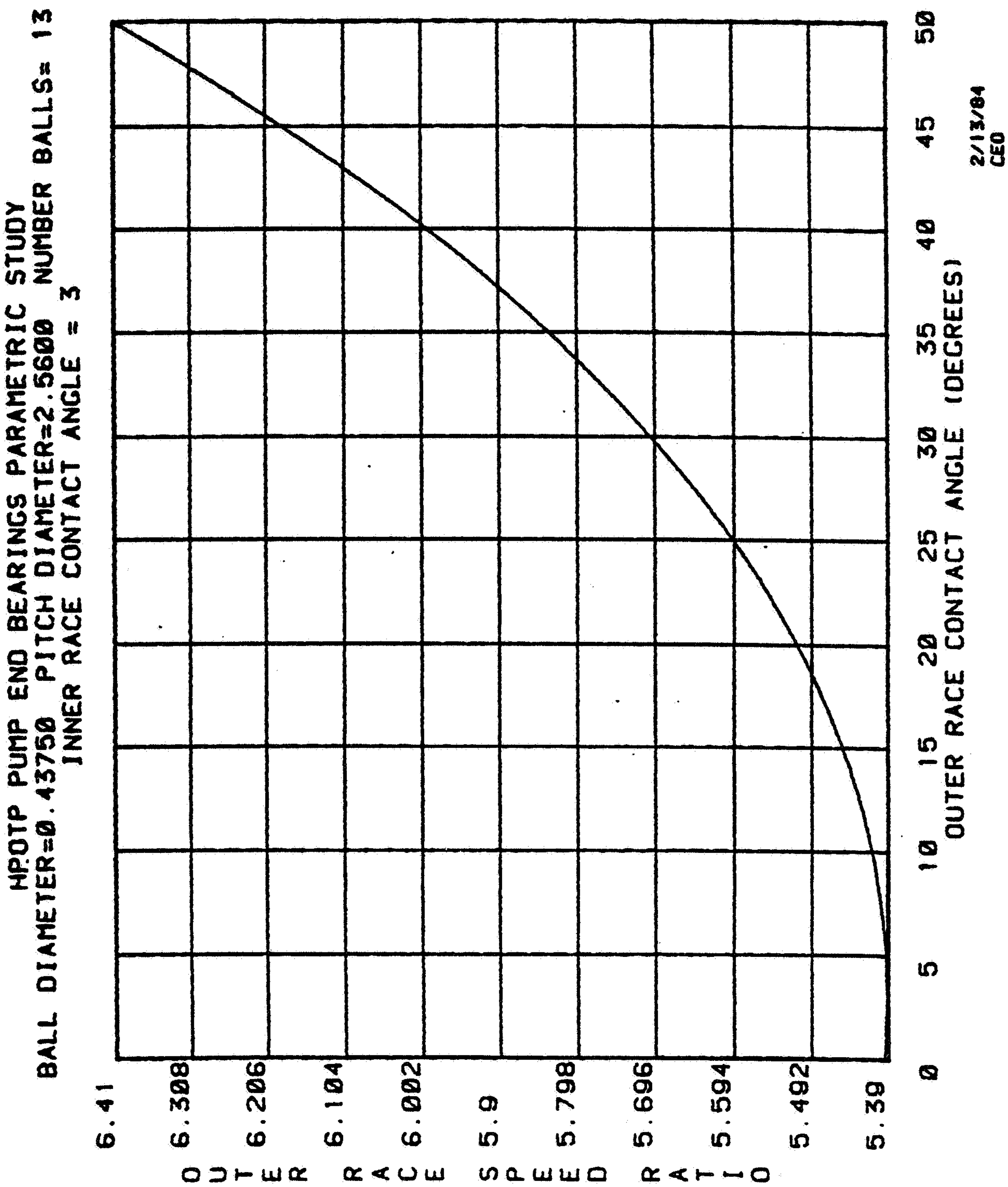
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
3.23
3.191
3.152
3.113
3.074
3.035
2.996
2.957
2.918
2.879
2.84
BALL SPIN RATIO
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO


HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
BALL SPIN RATIO
3.08
3.056
3.032
3.008
2.984
2.96
2.936
2.912
2.888
2.864
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

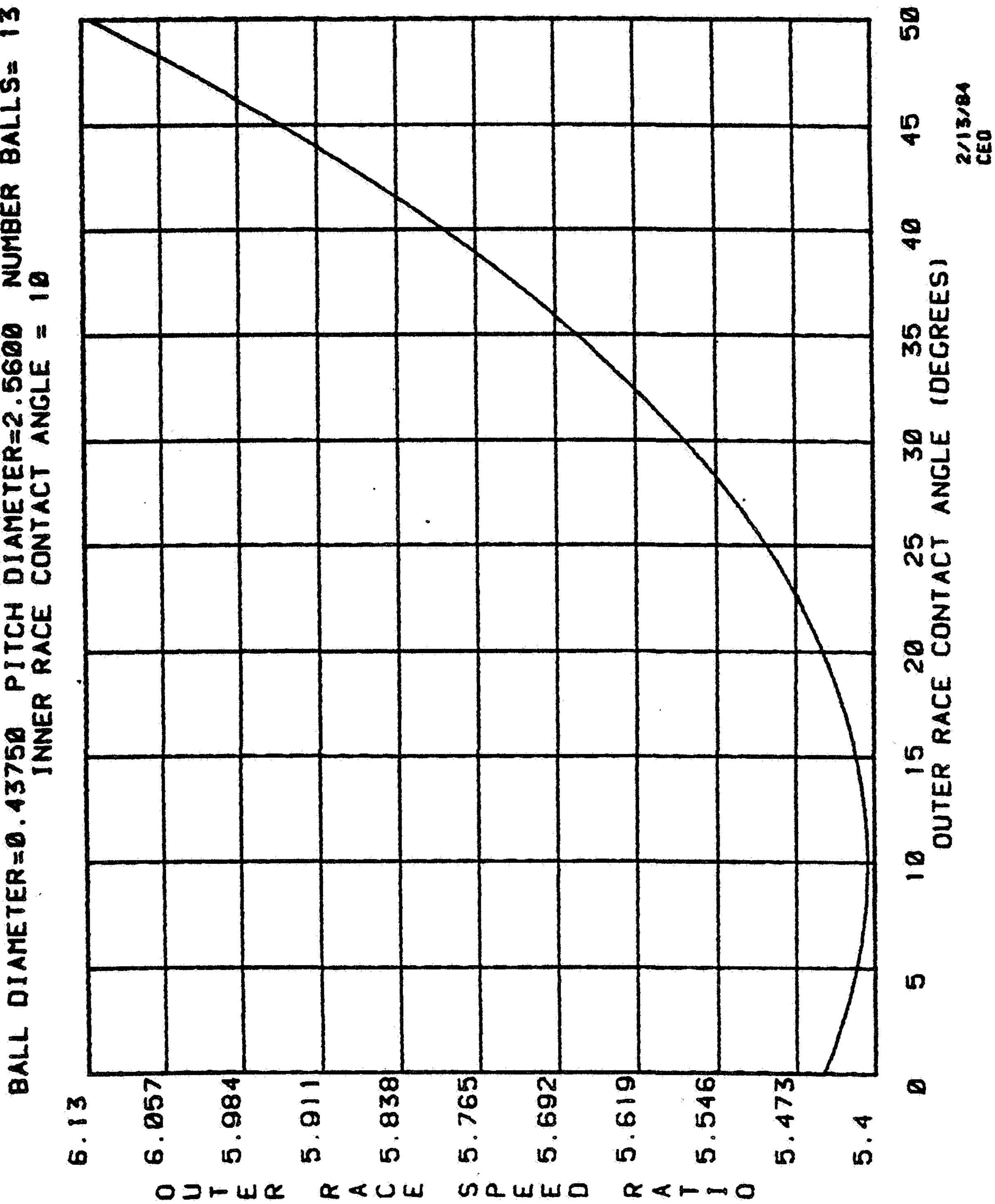

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
BALL SPIN RATIO
2.97
2.957
2.944
2.931
2.918
2.905
2.892
2.879
2.866
2.853
2.84
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO



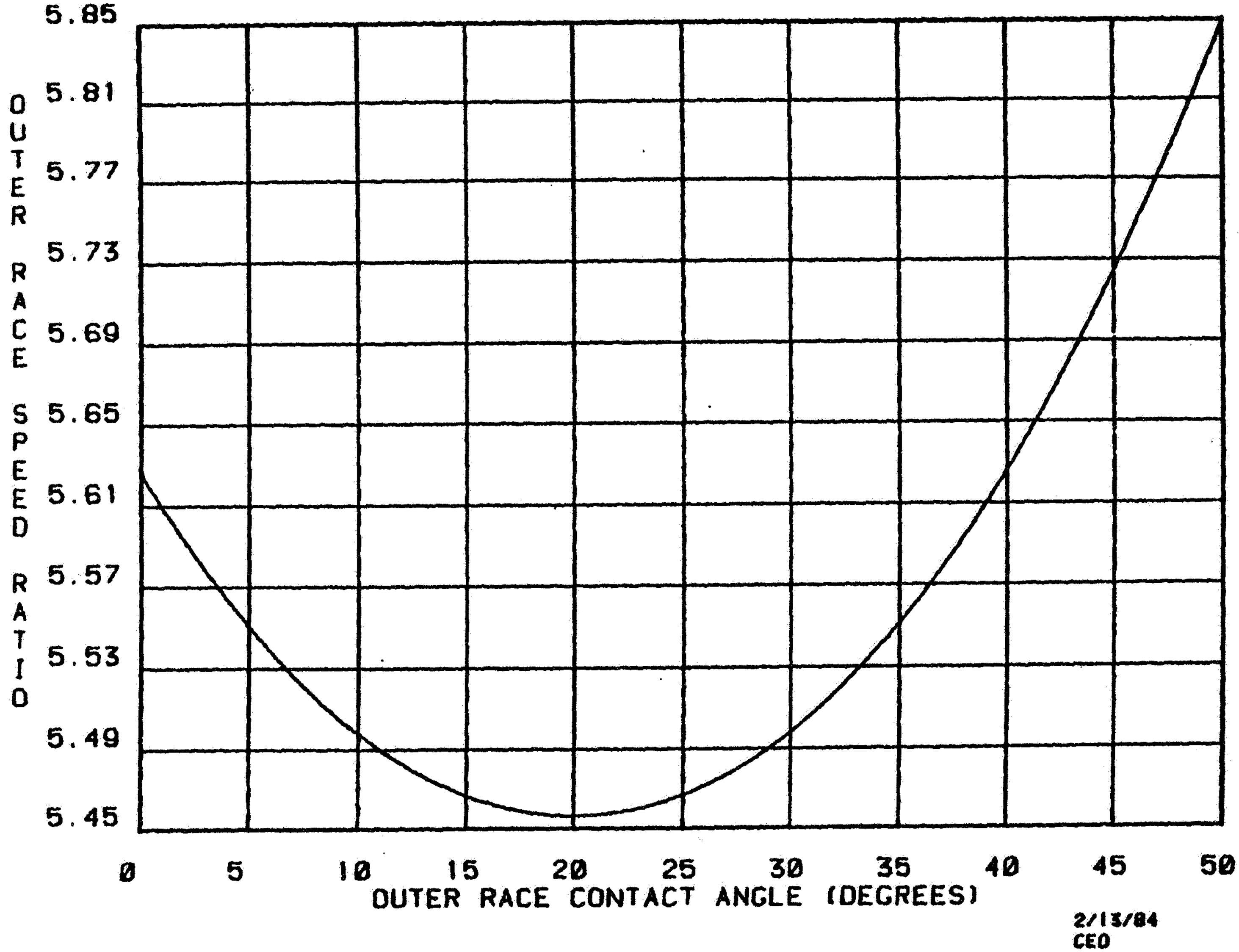
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
BALL SPIN RATIO
3.13
3.102
3.074
3.046
3.018
2.99
2.962
2.934
2.906
2.878
2.85
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

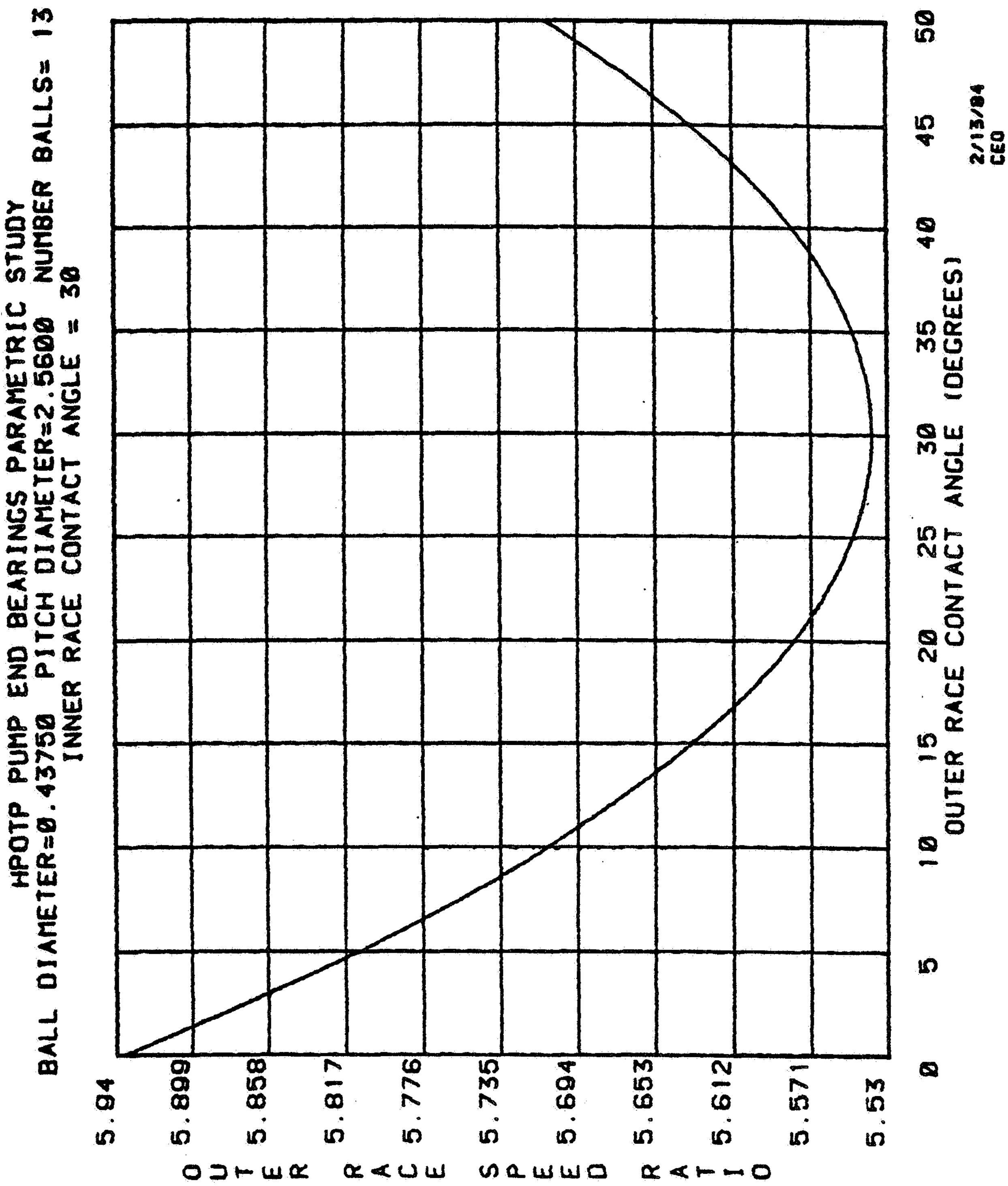


HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
OUTER RACE SPEED RATIO
6.41
6.308
6.206
6.104
6.002
5.9
5.798
5.696
5.594
5.492
5.39
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

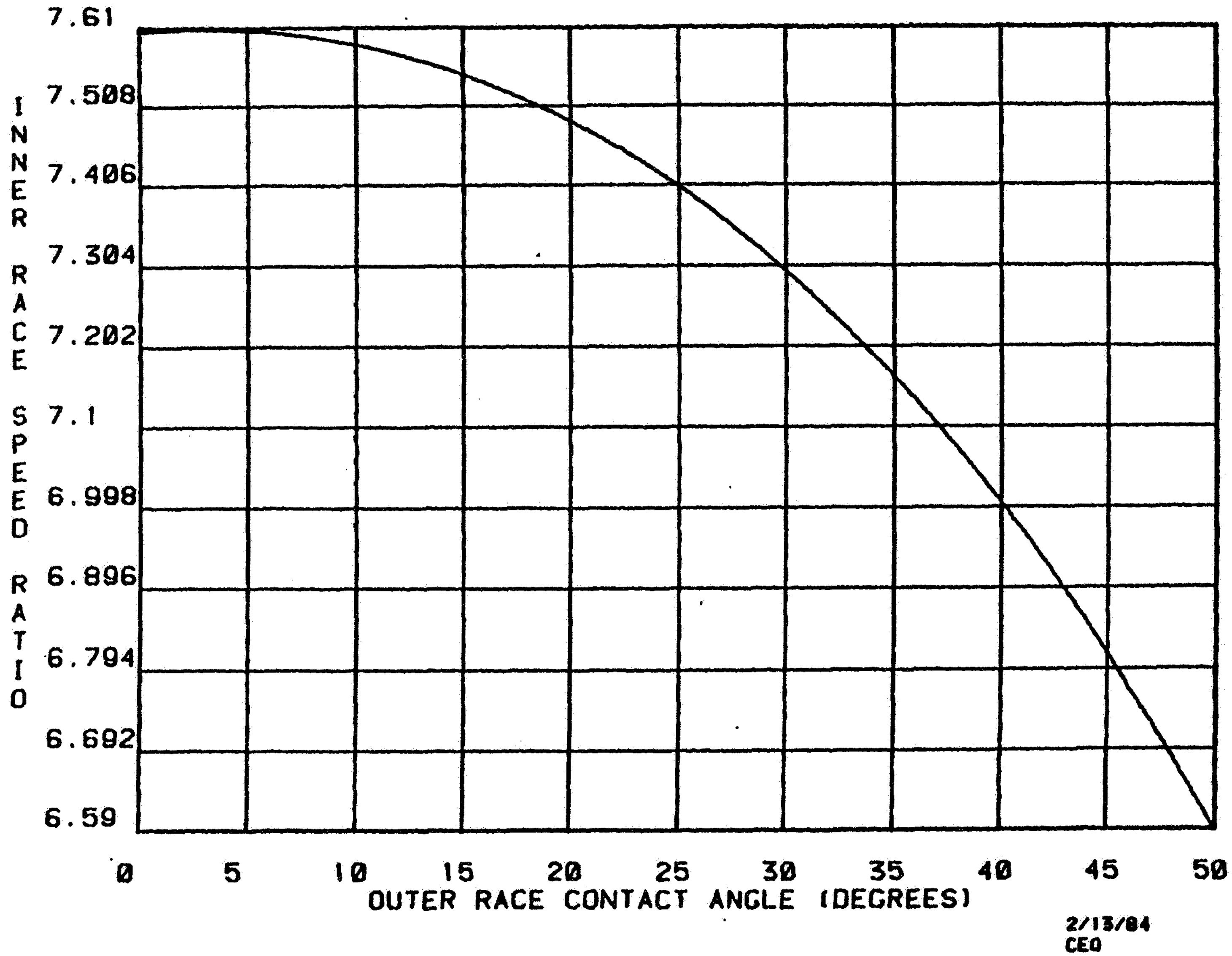

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10
OUTER RACE SPEED RATIO
6.13
6.057
5.984
5.911
5.838
5.765
5.692
5.619
5.546
5.473
5.4
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20

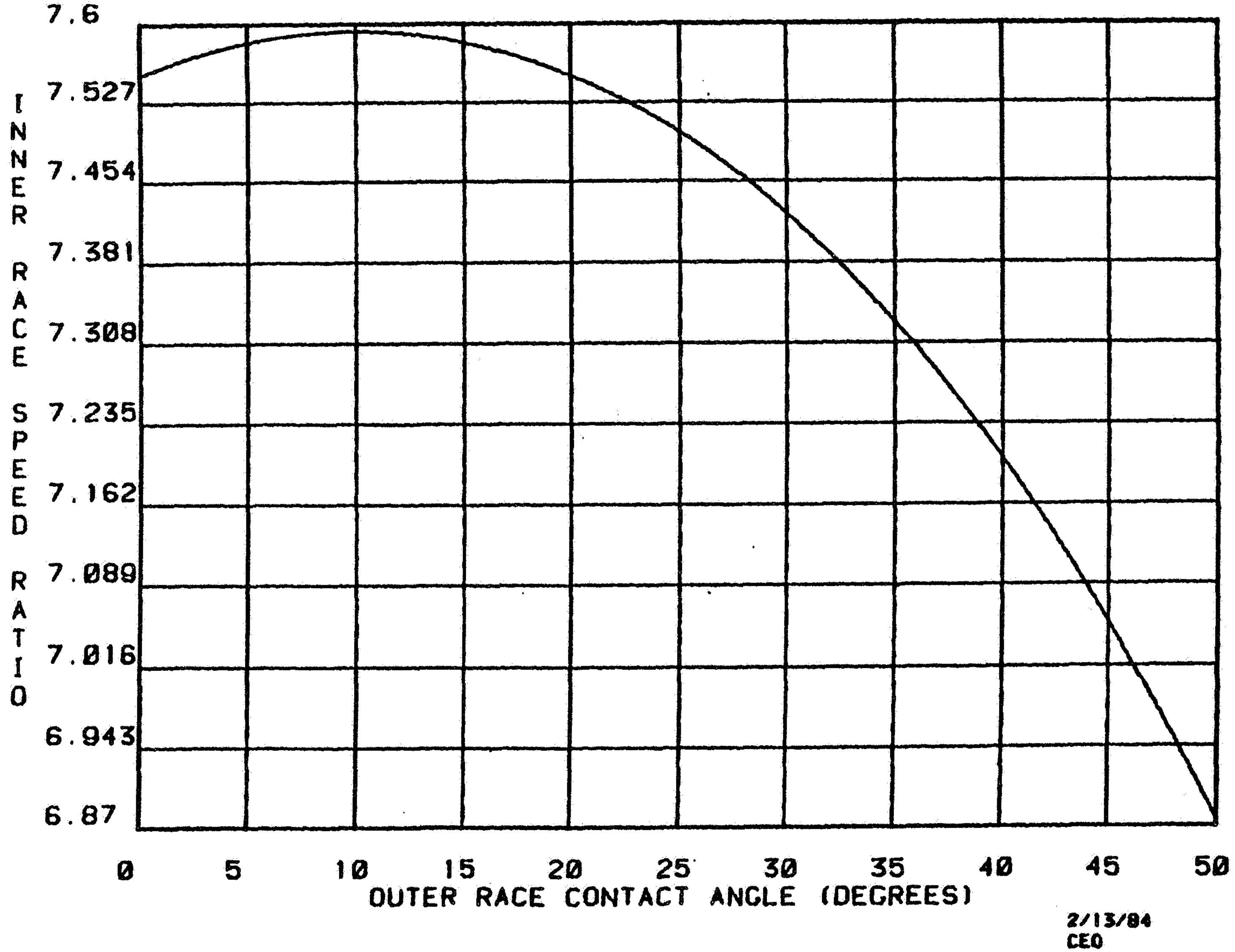


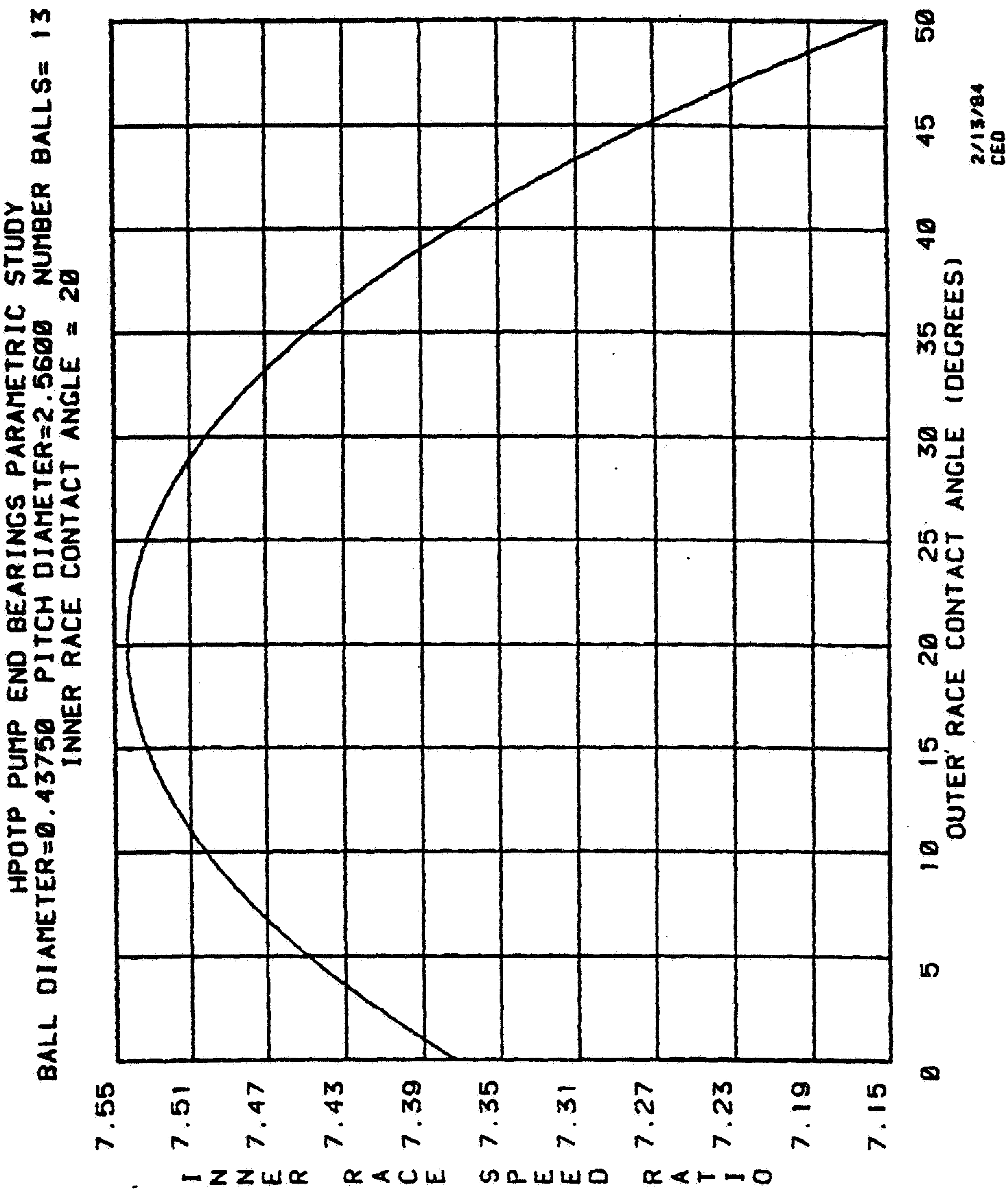

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30
OUTER RACE SPEED RATIO
5.94
5.899
5.858
5.817
5.776
5.735
5.694
5.653
5.612
5.571
5.53
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CEO

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3



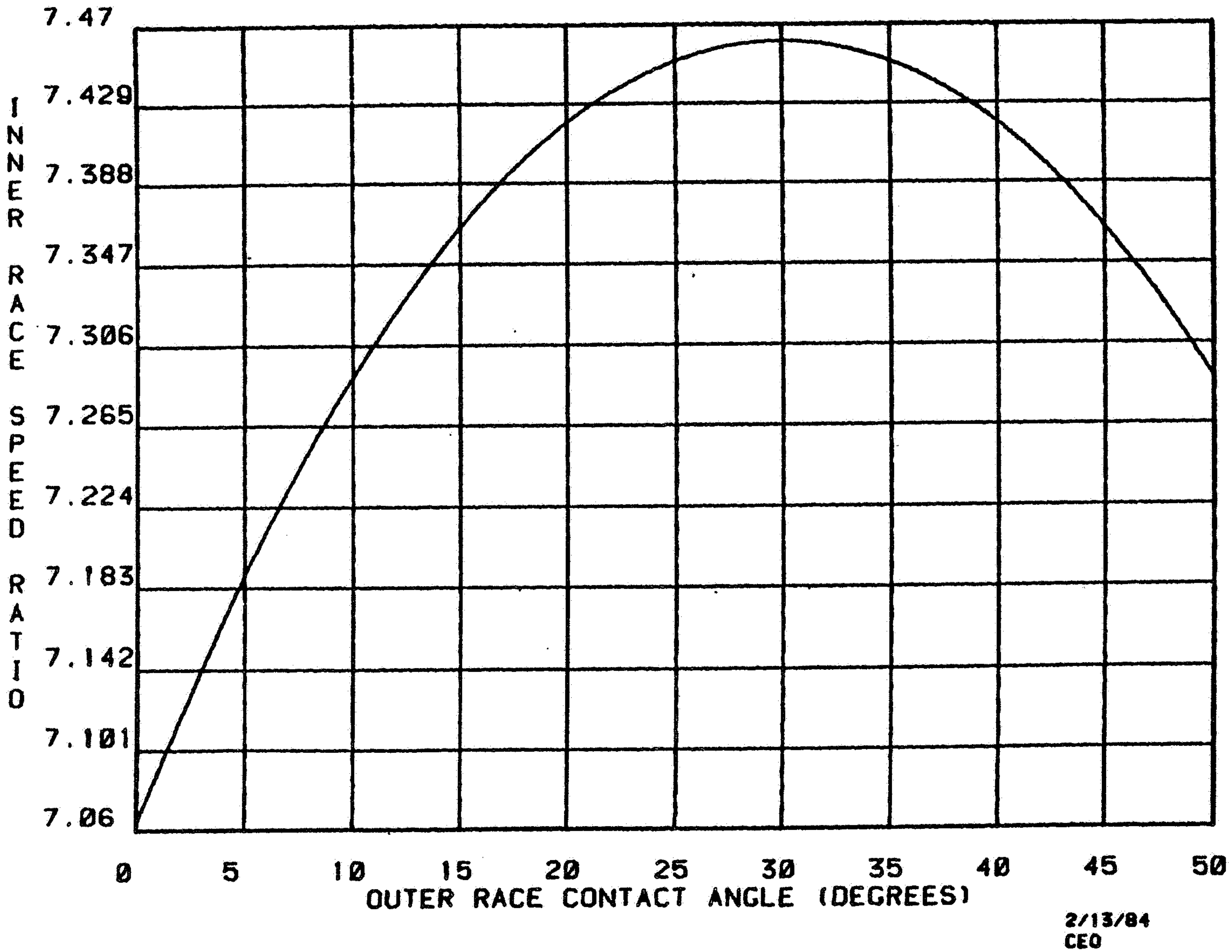
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 10





HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 20
INNER RACE SPEED RATIO
7.55
7.51
7.47
7.43
7.39
7.35
7.31
7.27
7.23
7.19
7.15
0
5
10
15
20
25
30
35
40
45
50
OUTER RACE CONTACT ANGLE (DEGREES)
2/13/84
CED

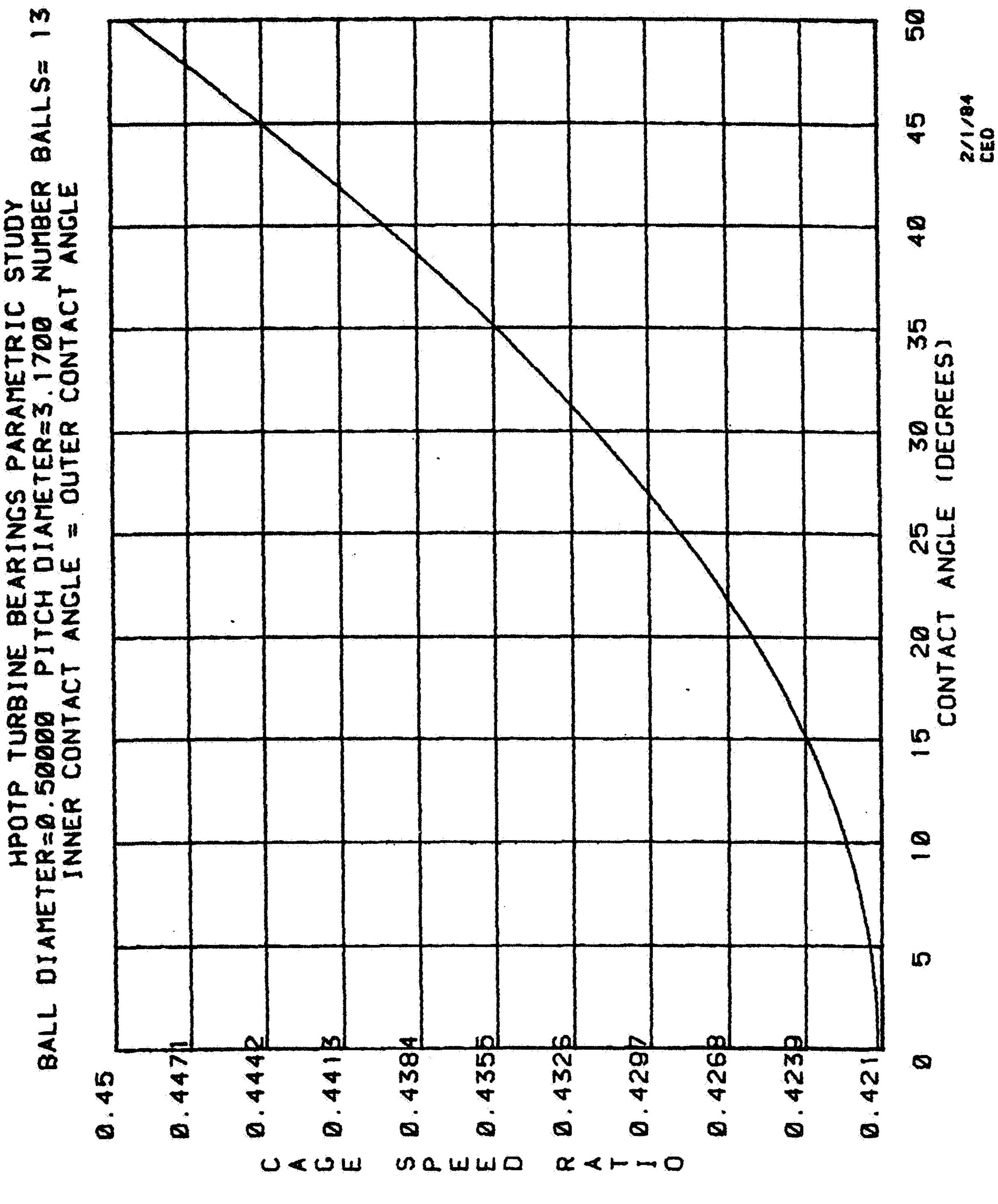
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 30



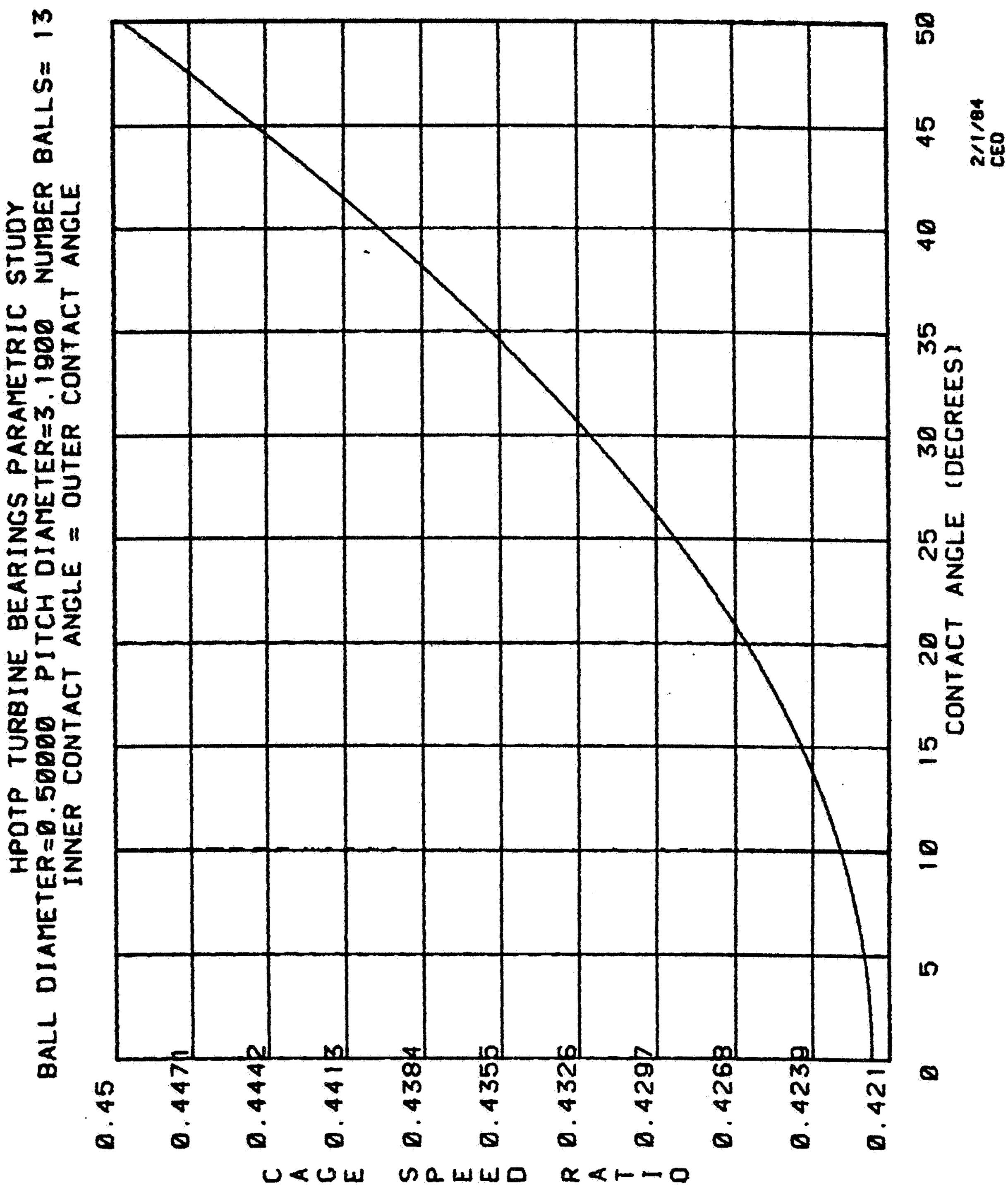
C-4

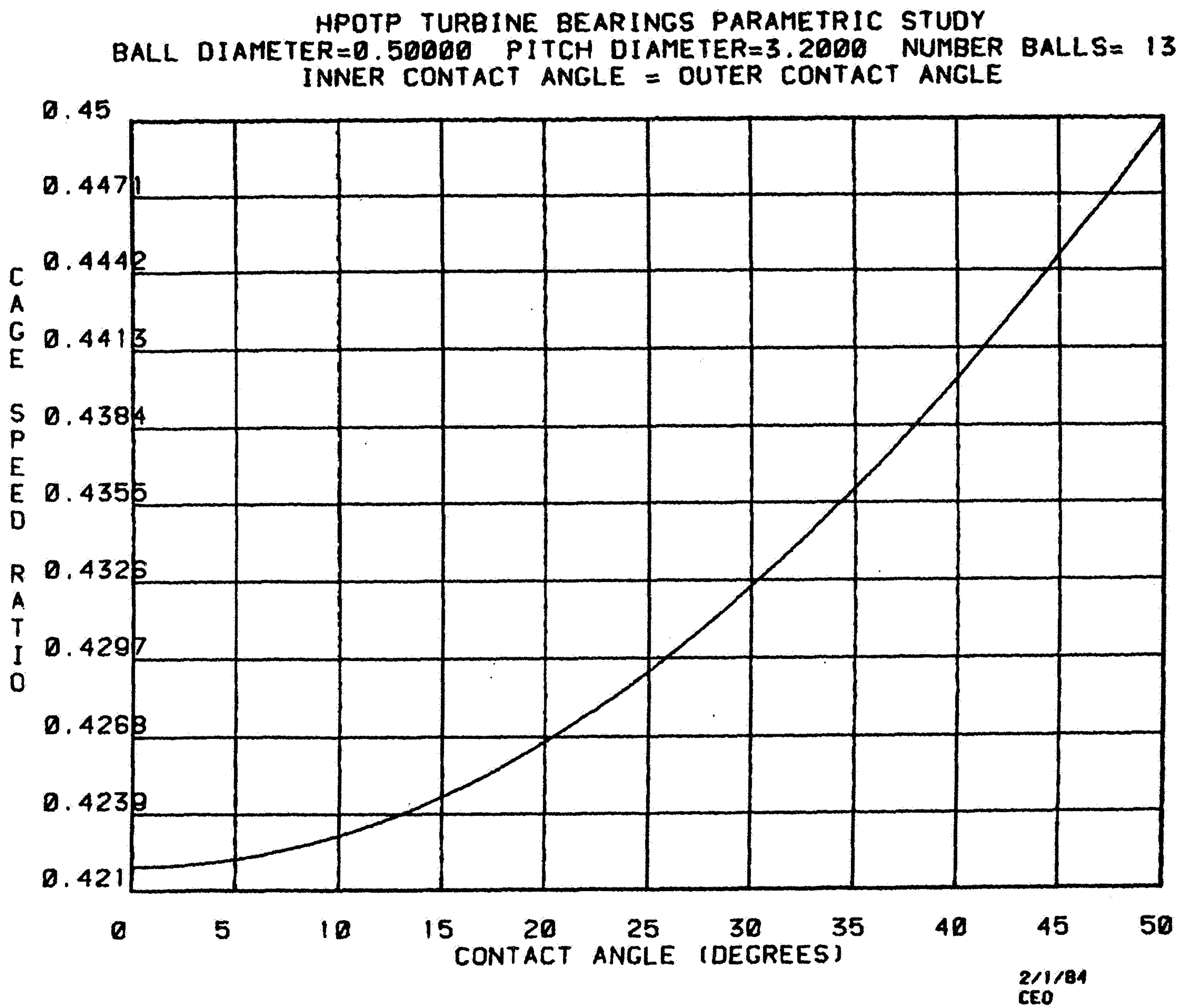
SPEED RATIO OF
DIFFERENT PITCH DIAMETERS
OF HPOTP TURBINE BEARINGS

Ball Diameter	=	0.50 inch
Pitch Diameter	=	3.17, 3.19, and 3.20 inches
Number of Balls	=	13
Inner Contact Angle	=	Outer Contact Angle

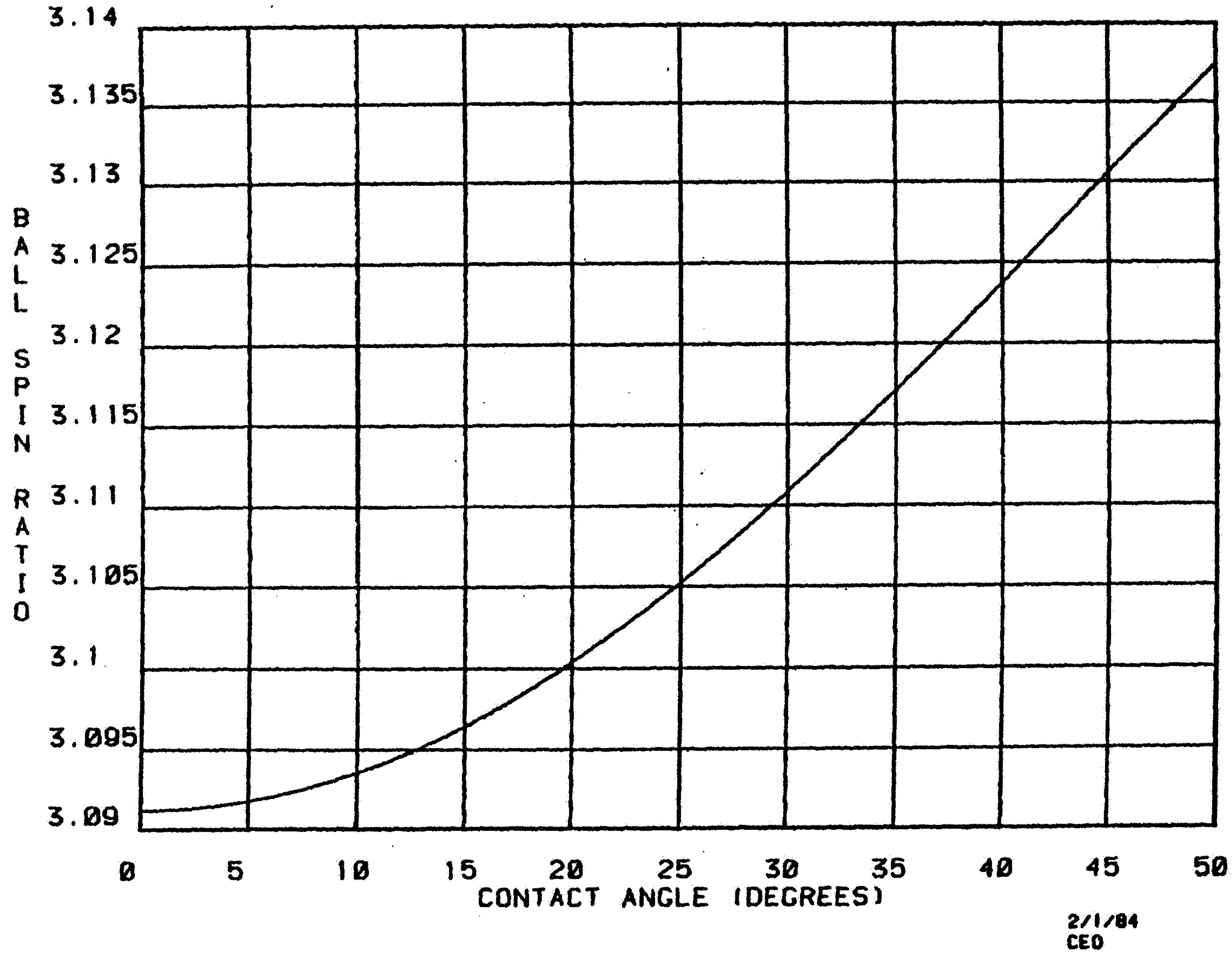


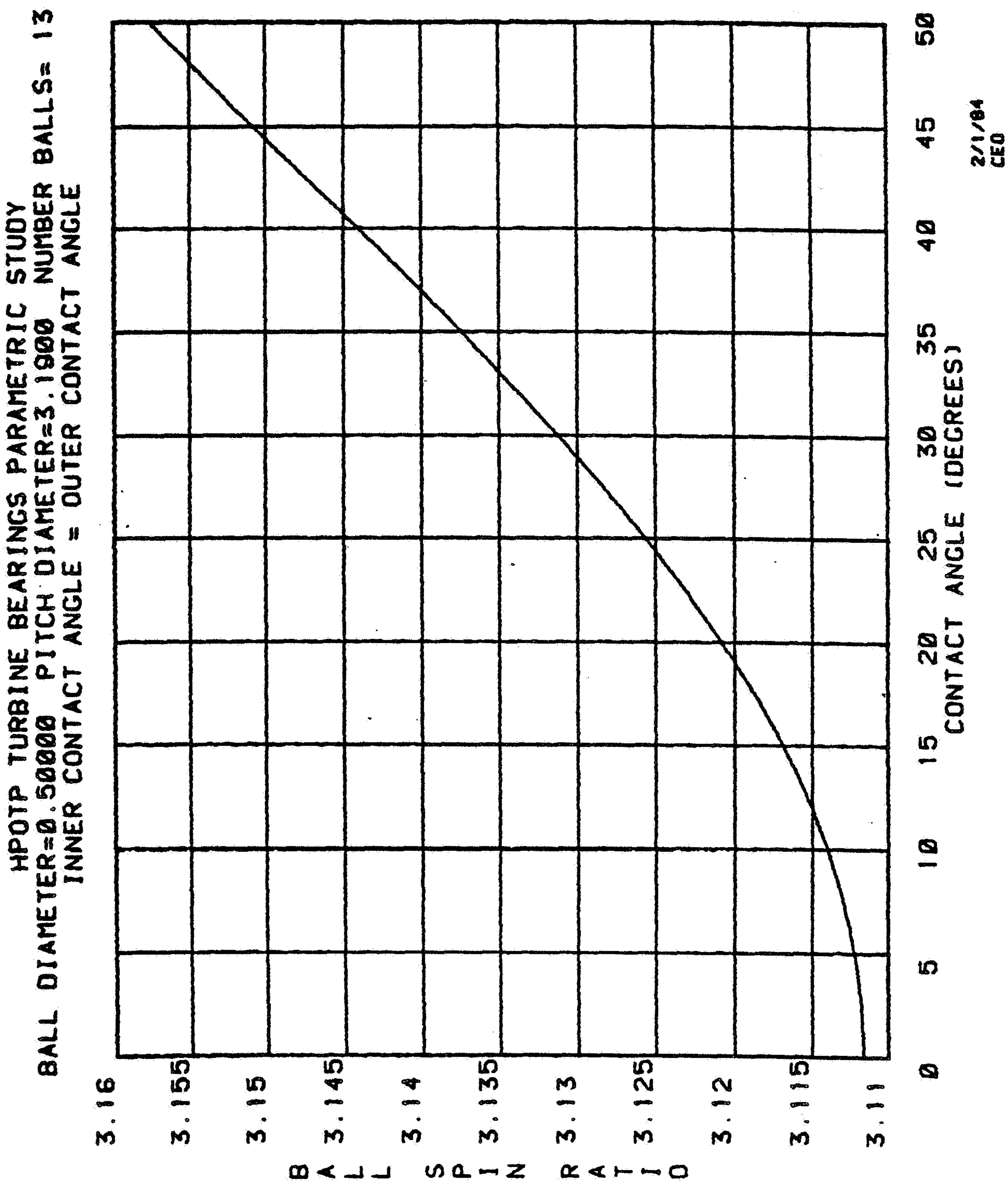
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1700 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.45
0.4471
0.4442
0.4413
0.4384
0.4355
0.4326
0.4297
0.4268
0.4239
0.421
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1900 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.45
0.4471
0.4442
0.4413
0.4384
0.4355
0.4326
0.4297
0.4268
0.4239
0.421
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

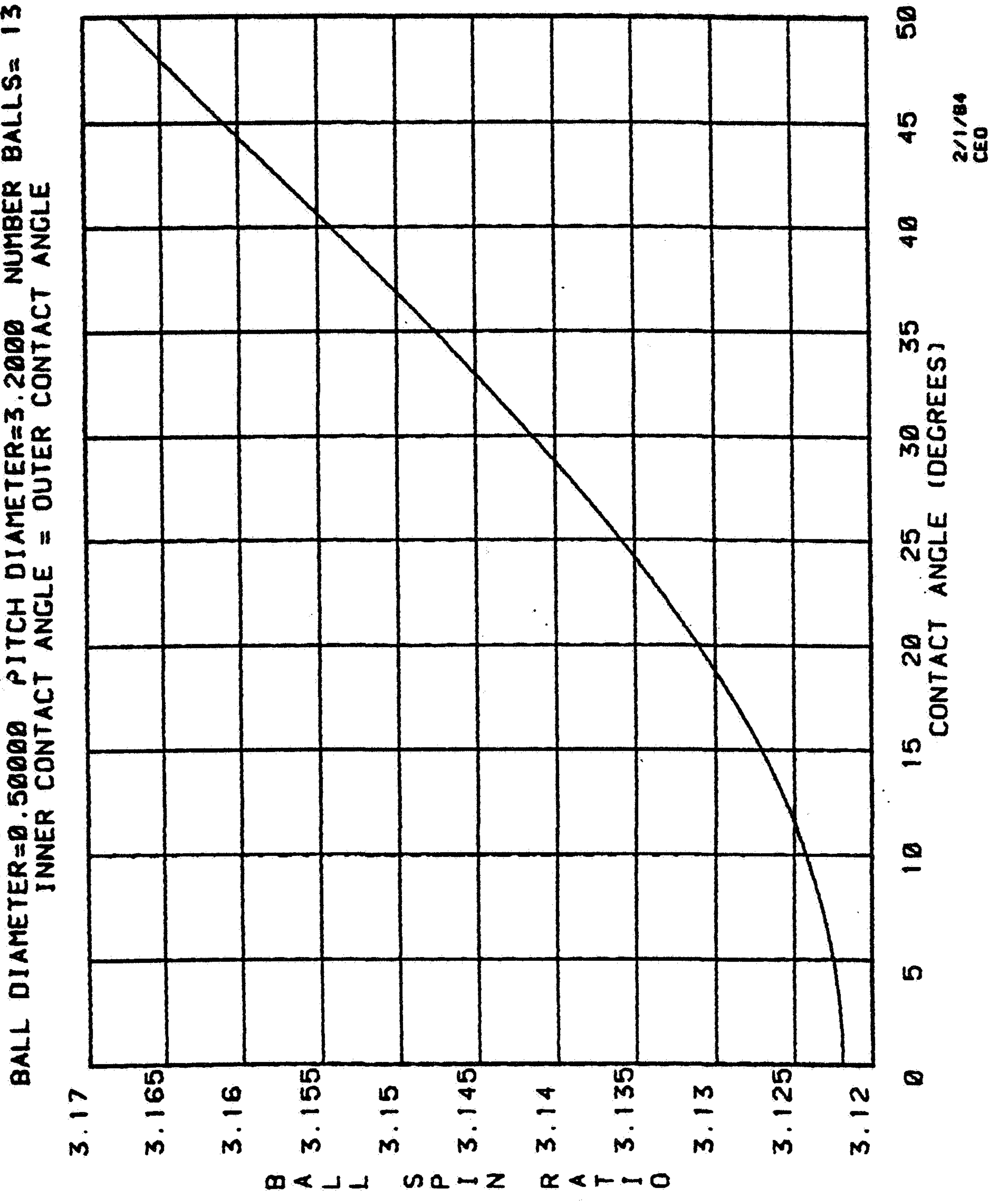

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.2000 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.45
0.4471
0.4442
0.4413
0.4384
0.4355
0.4326
0.4297
0.4268
0.4239
0.421
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1700 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE

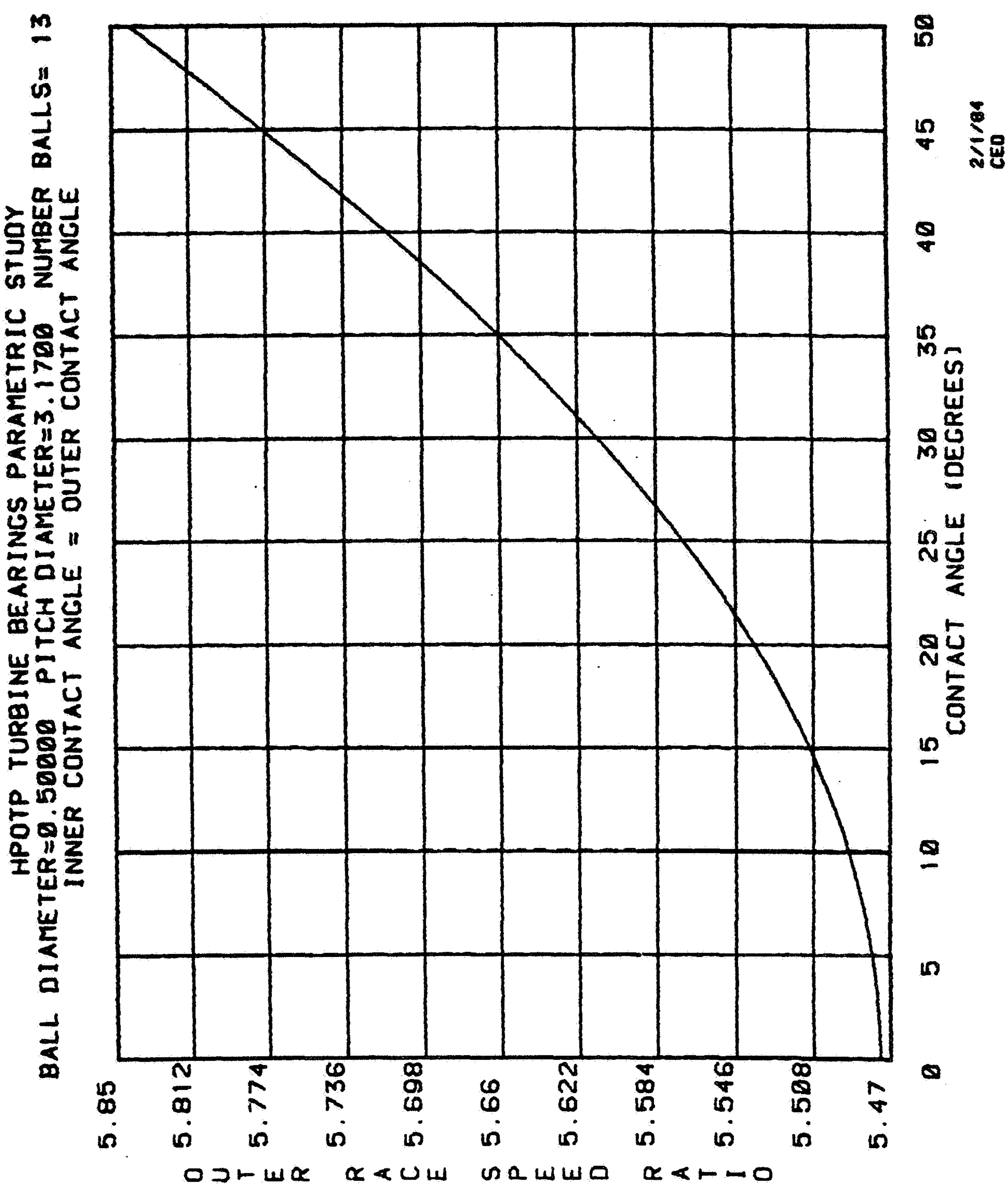


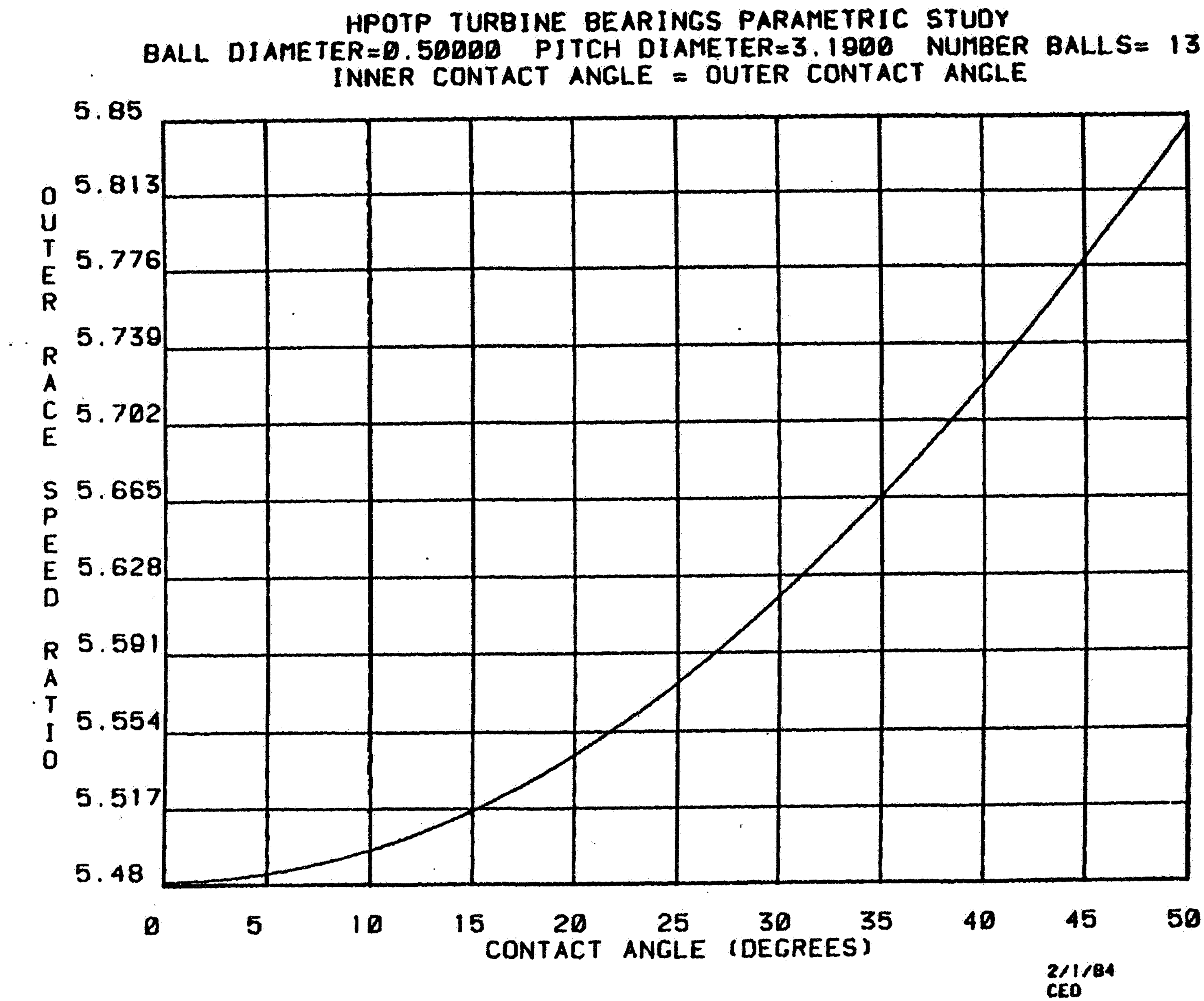


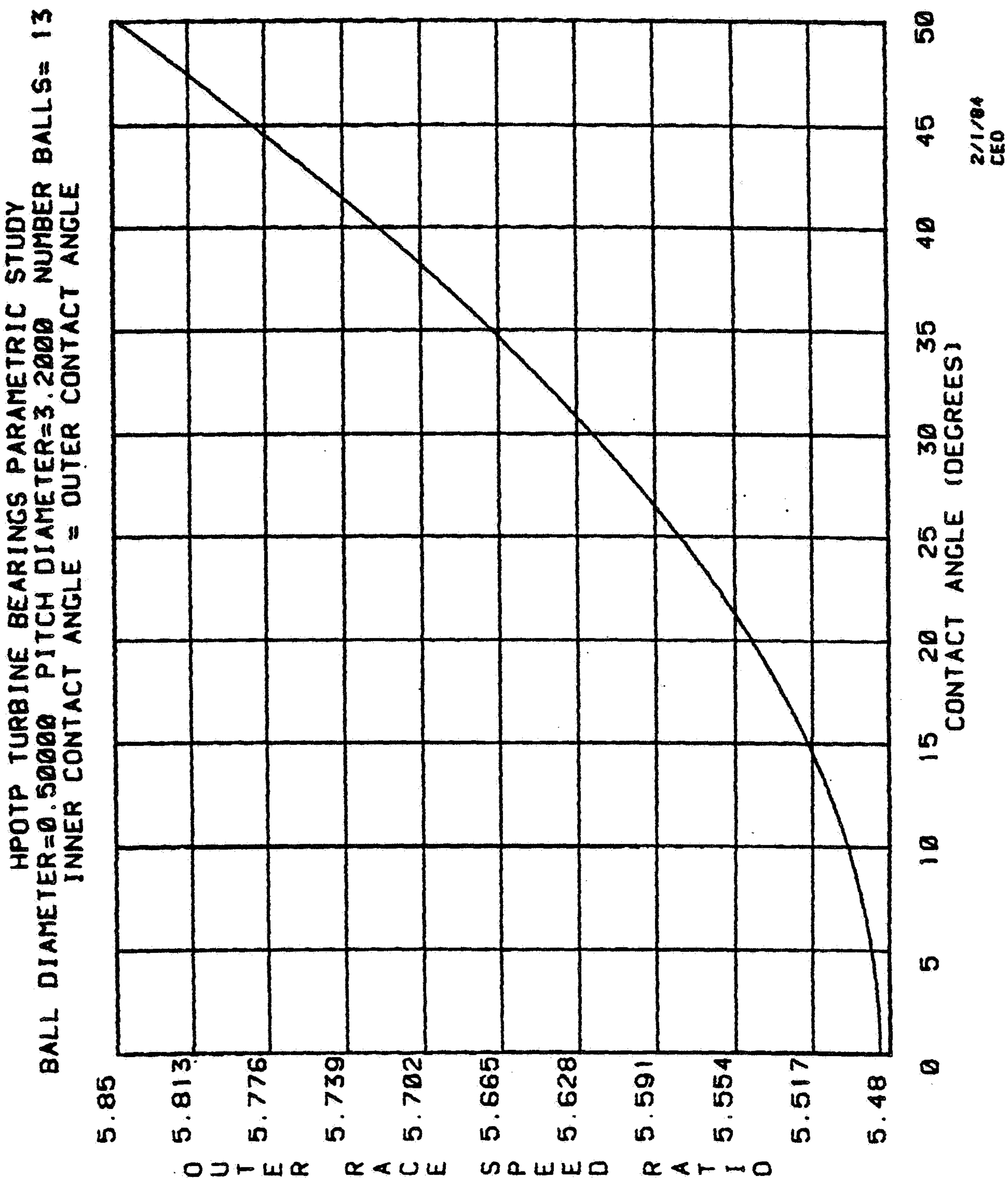
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1900 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
3.11
3.115
3.12
3.125
3.13
3.135
3.14
3.145
3.15
3.155
3.16
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO



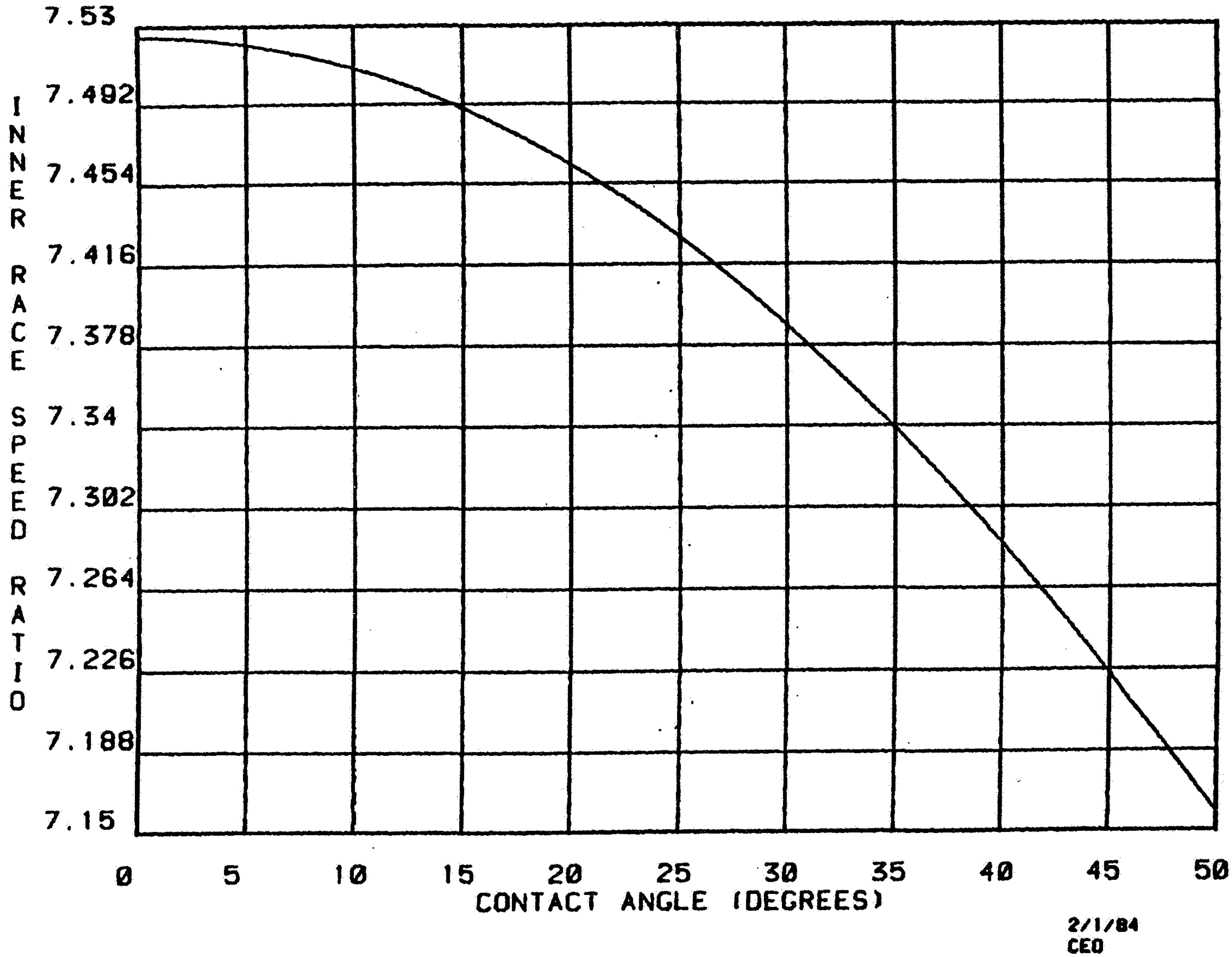
HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.2000 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
3.17
3.165
3.16
3.155
3.15
3.145
3.14
3.135
3.13
3.125
3.12
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

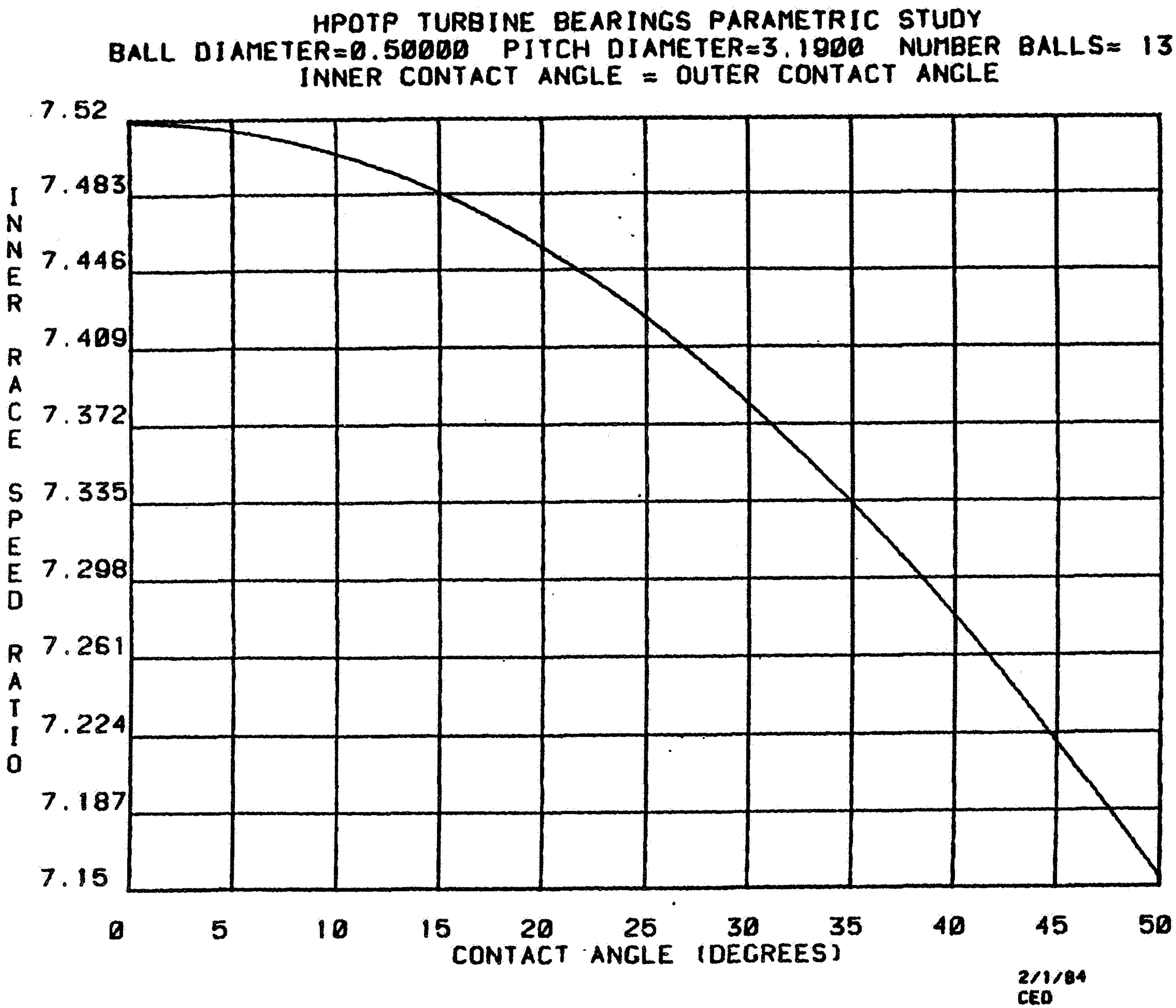

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1700 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
5.85
5.812
5.774
5.736
5.698
5.66
5.622
5.584
5.546
5.508
5.47
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED

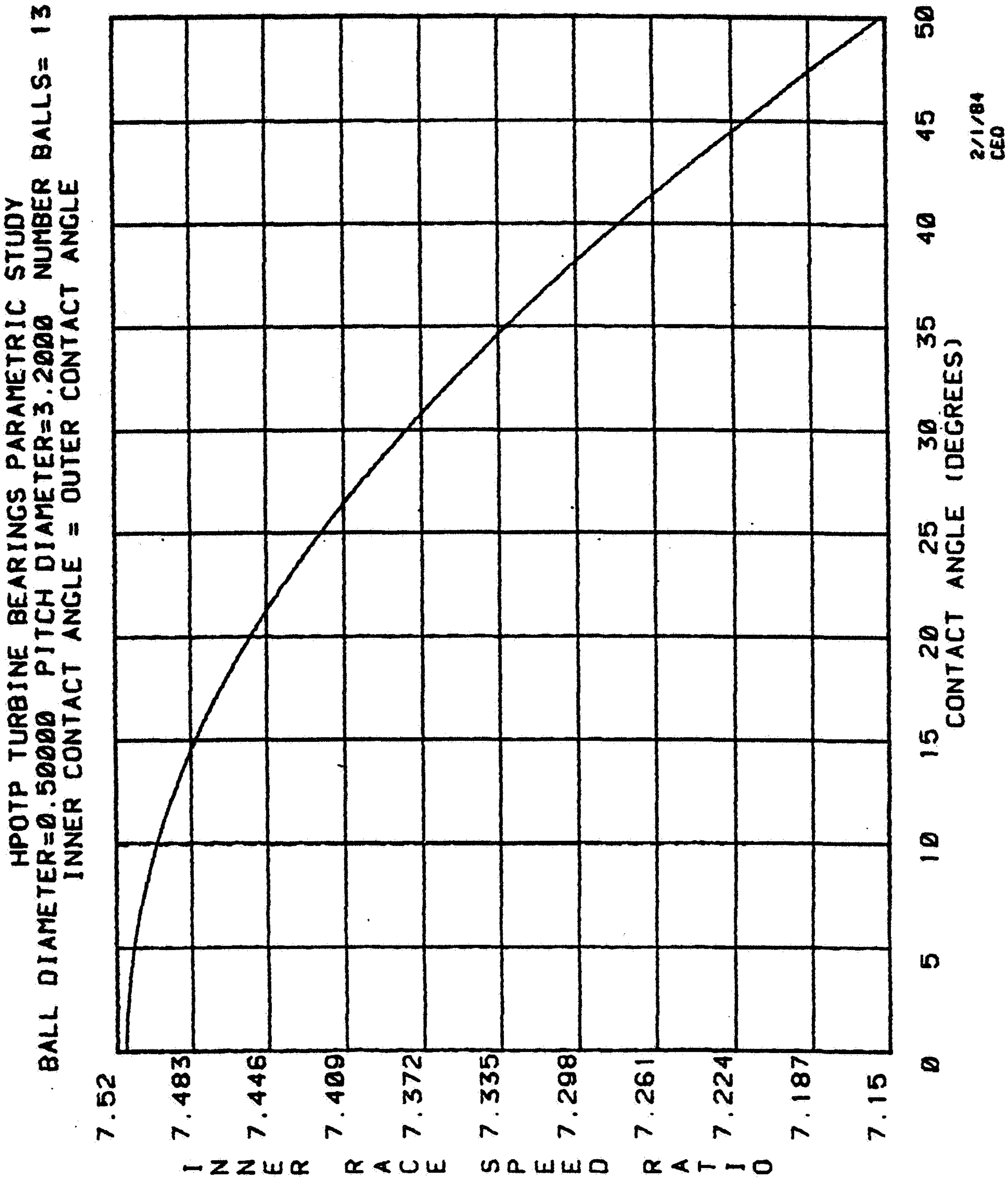

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1900 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
5.85
5.813
5.776
5.739
5.702
5.665
5.628
5.591
5.554
5.517
5.48
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.2000 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
5.85
5.813
5.776
5.739
5.702
5.665
5.628
5.591
5.554
5.517
5.48
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1700 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE




HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1900 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
INNER RACE SPEED RATIO
7.52
7.483
7.446
7.409
7.372
7.335
7.298
7.261
7.224
7.187
7.15
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.2000 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
INNER RACE SPEED RATIO
7.52
7.483
7.446
7.409
7.372
7.335
7.298
7.261
7.224
7.187
7.15
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

SPEED RATIO WITH DYNAMIC EFFECTS NEGLECTED

Charts of this section are for simple rolling motion, which is only applicable for the case of slow rotational speed and/or applied radial load of large magnitude.[2] The dynamic effects were neglected: i.e., outer contact angle equal to inner contact angle. The equations for this case are as follows:

$$\text{Cage speed ratio} = 1/2\,(1 - D/d_m \cos\phi)$$

$$\text{Outer race speed ratio} = N_b/2\,(1 - D/d_m \cos\phi)$$

$$\text{Inner race speed ratio} = N_b/2\,(1 + D/d_m \cos\phi)$$

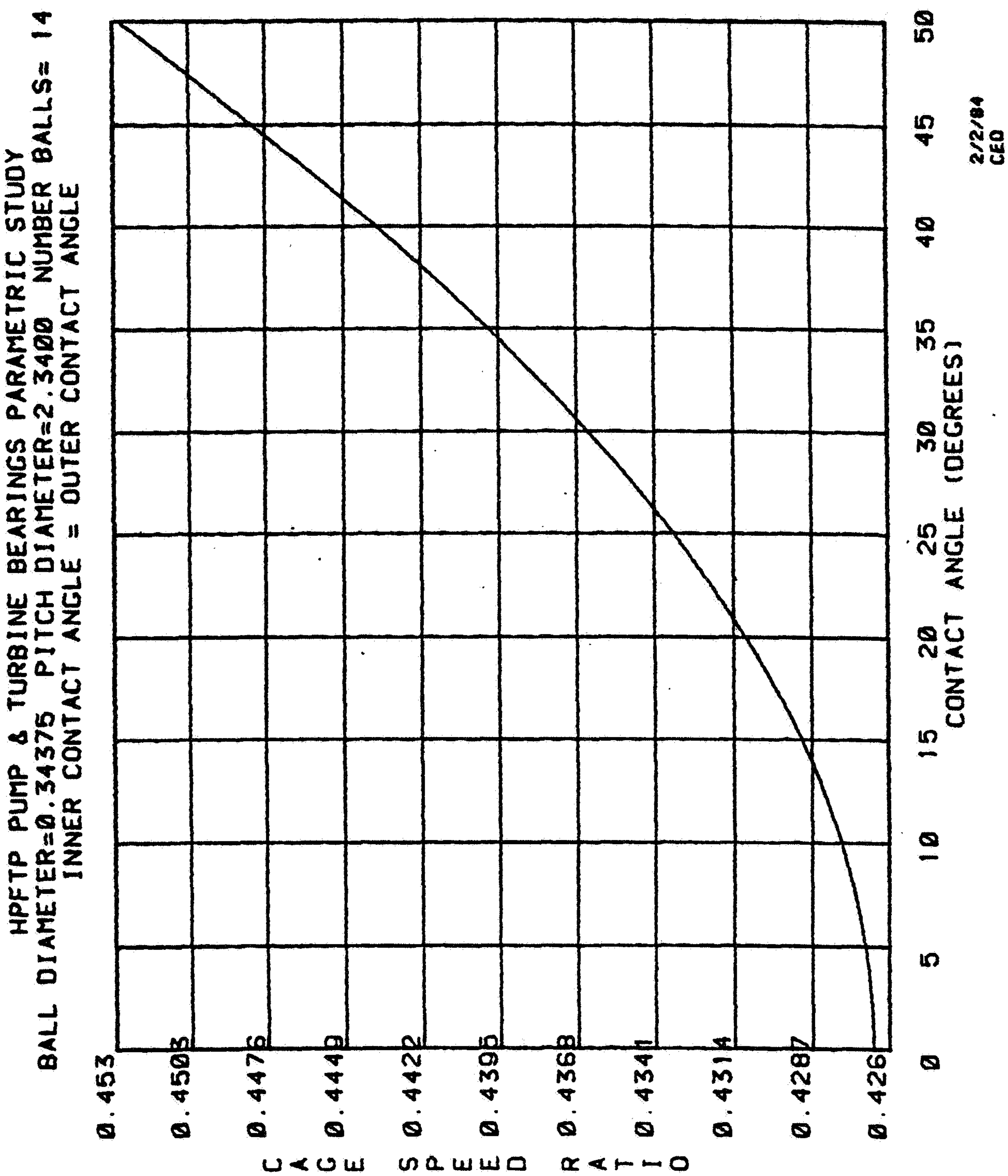
$$\text{Ball spin ratio} = 1/2\, d_m/D \left[1 - (D/d_m)^2 \cos^2\phi\right]$$

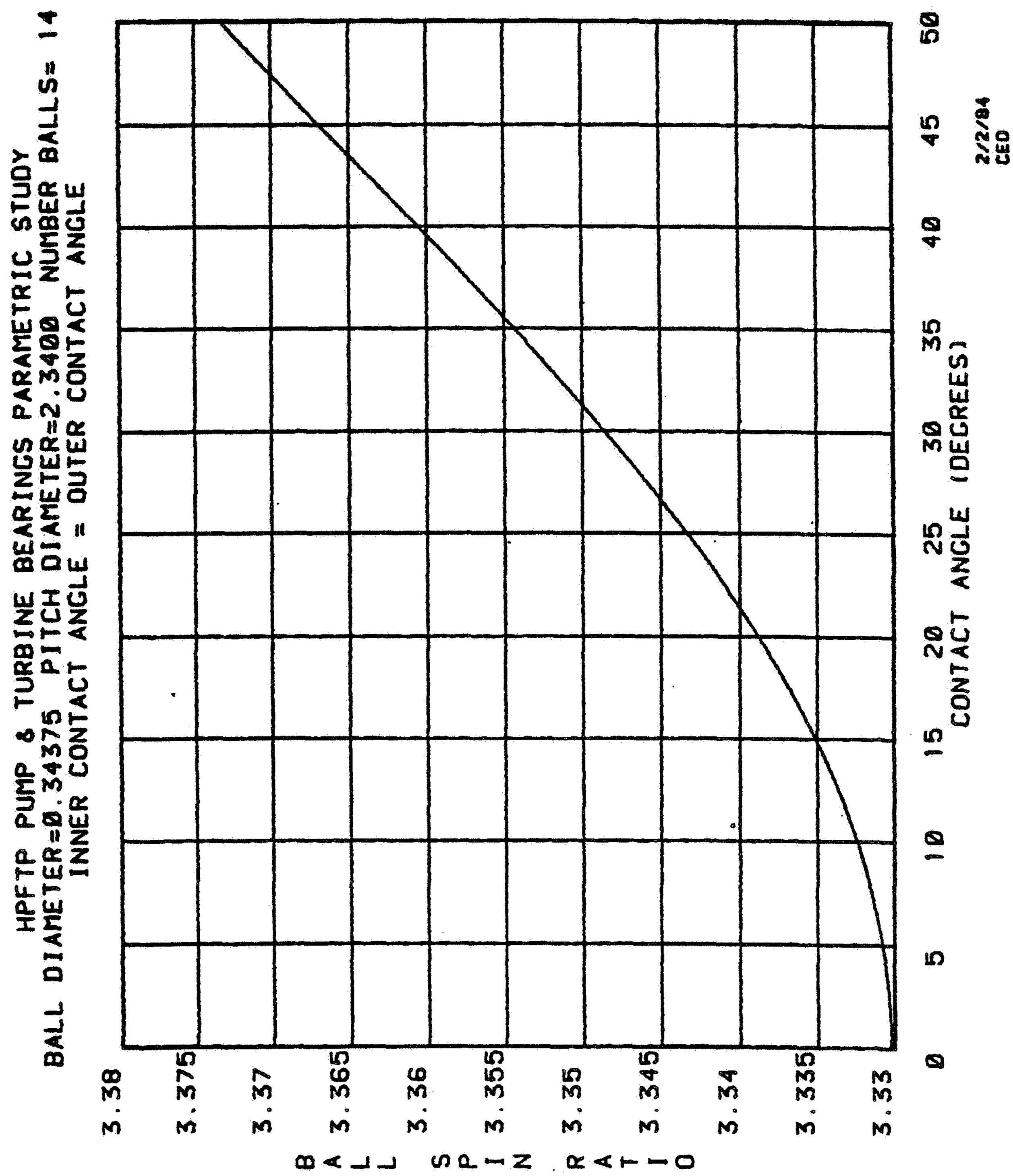
D = Ball diameter

d_m = Pitch diameter

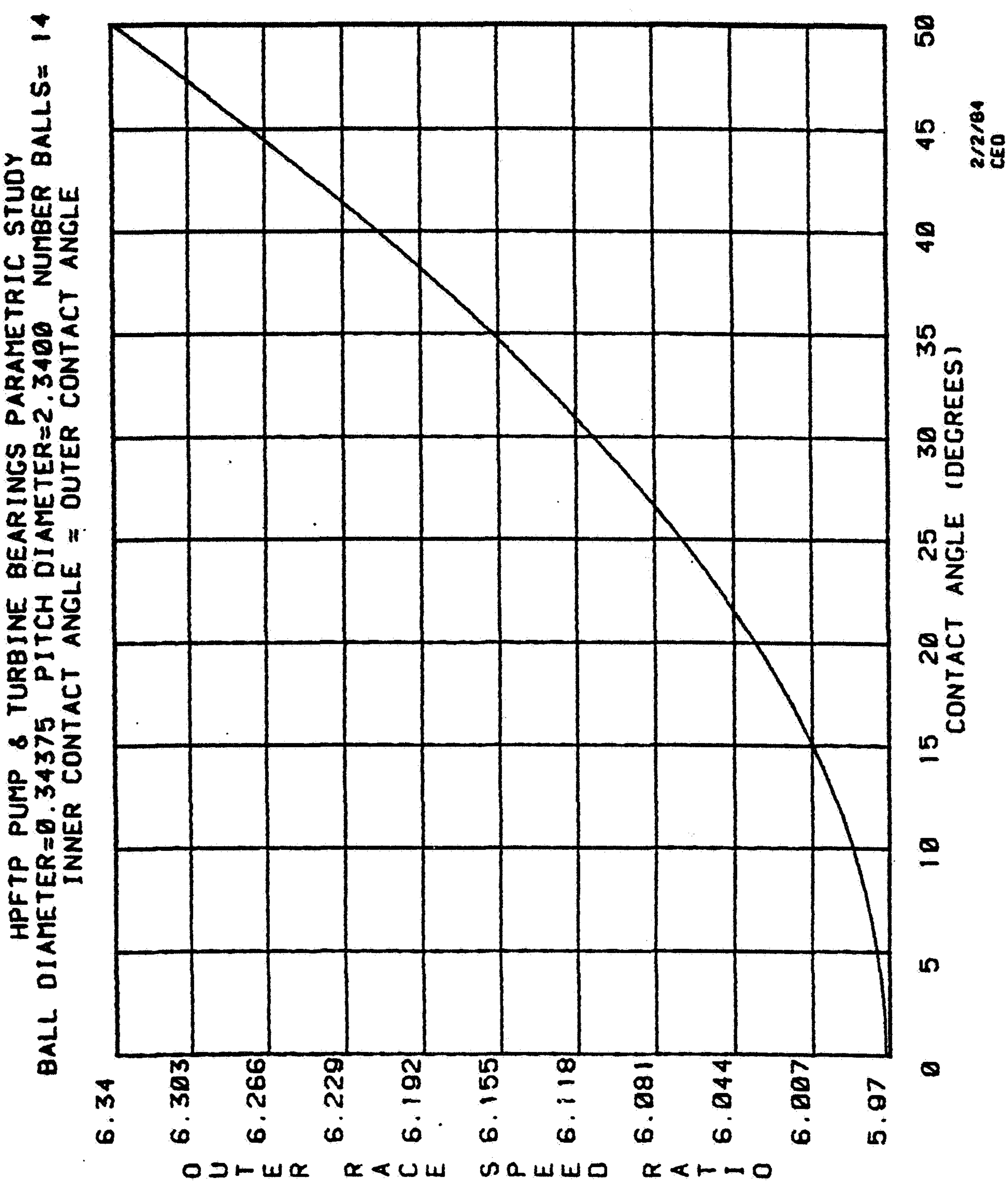
N_b = Number of balls

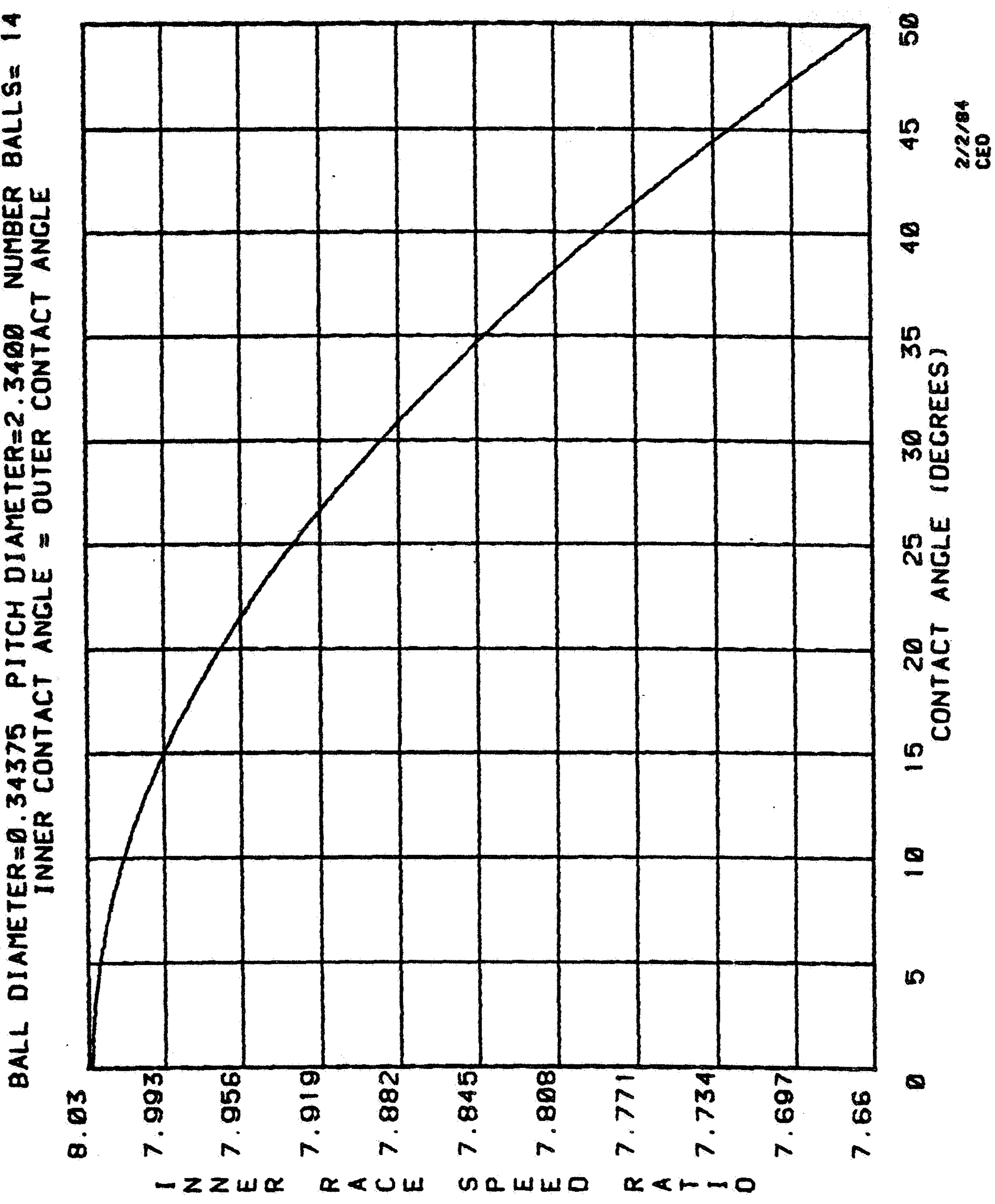
ϕ = Contact angle

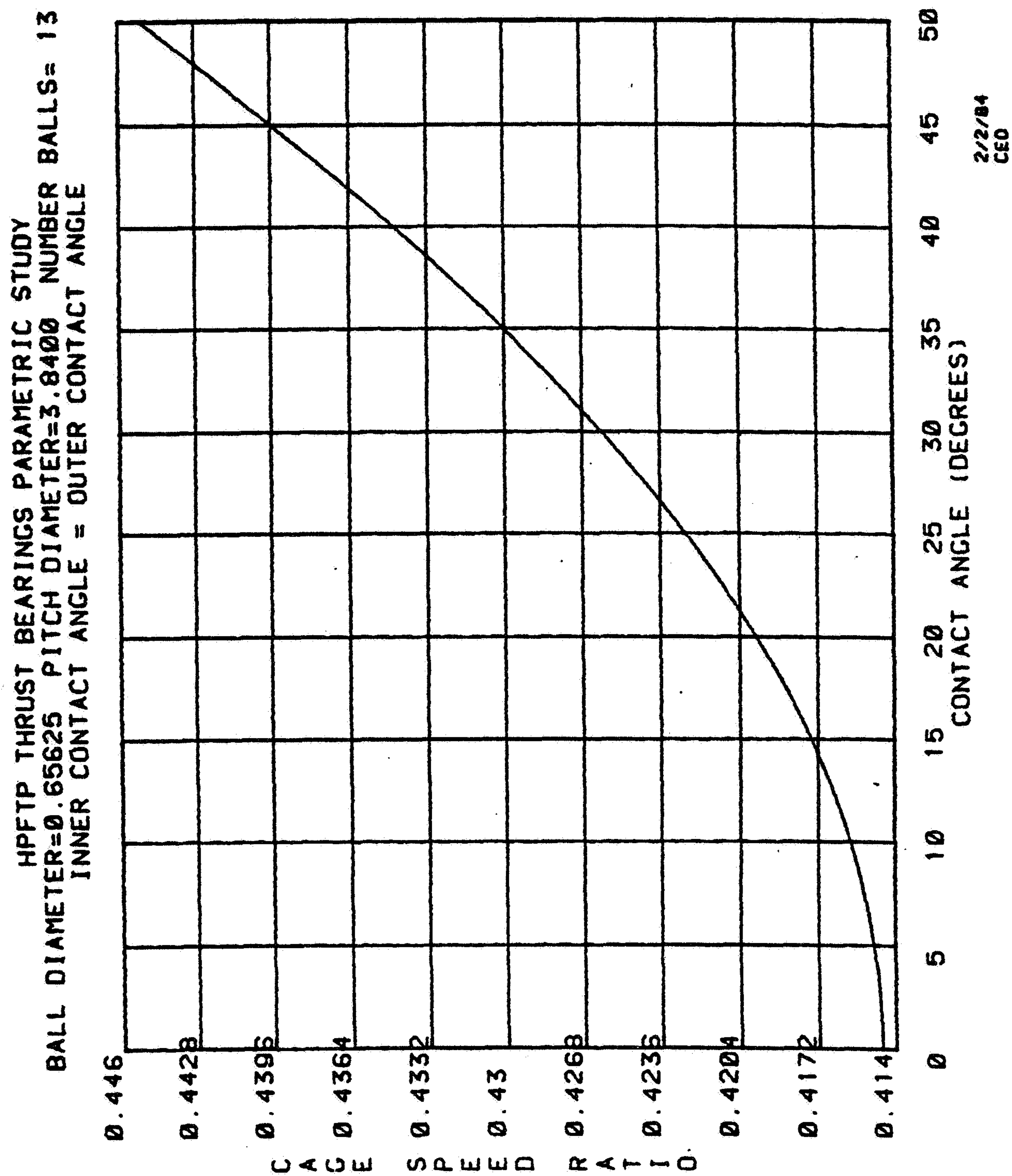

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.426
0.4287
0.4314
0.4341
0.4368
0.4395
0.4422
0.4449
0.4476
0.4503
0.453
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CED



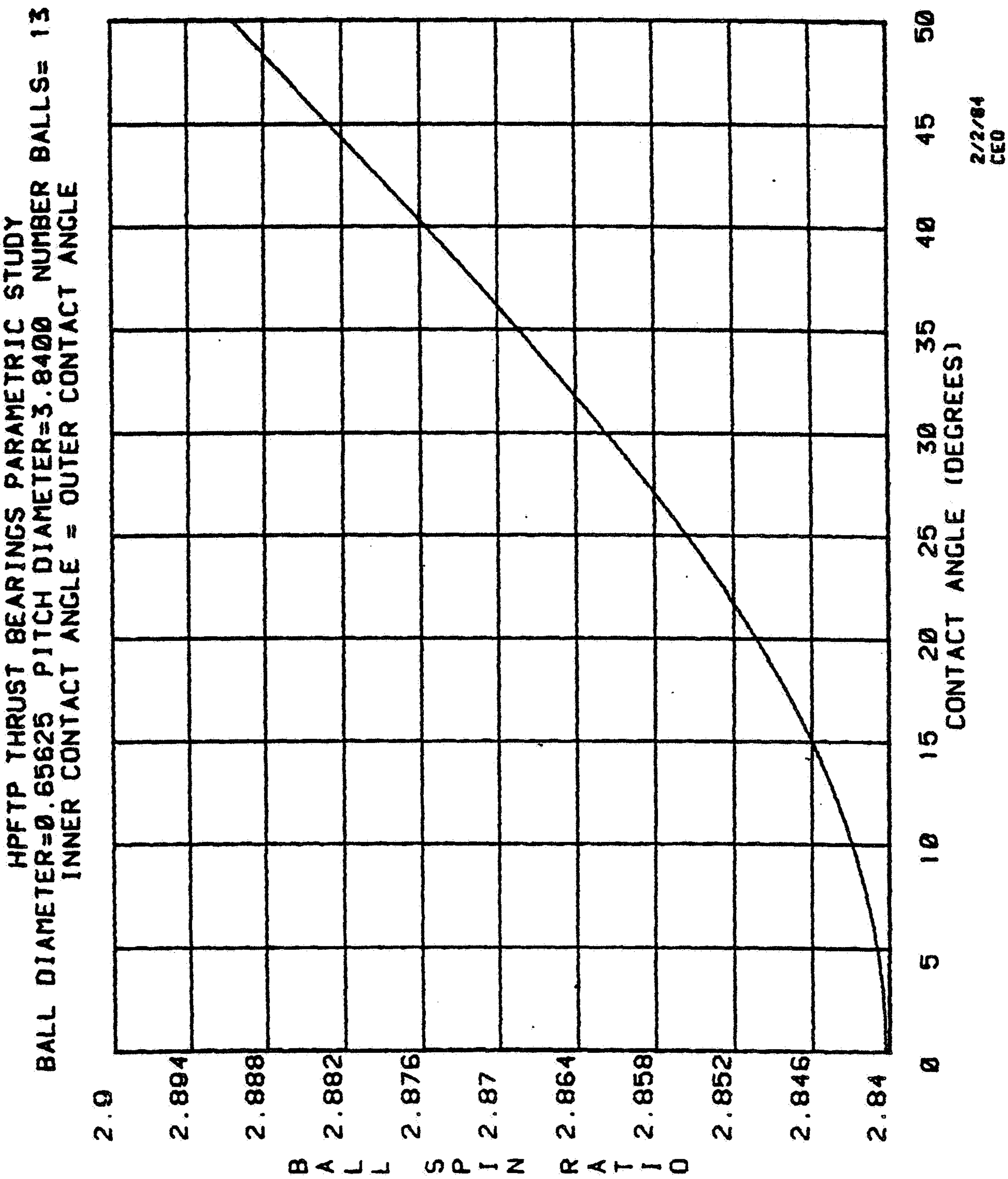
HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=Ø.34375 PITCH DIAMETER=2.340Ø NUMBER BALLS= 14
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
3.38
3.375
3.37
3.365
3.36
3.355
3.35
3.345
3.34
3.335
3.33
Ø
5
1Ø
15
20
25
3Ø
35
4Ø
45
5Ø
CONTACT ANGLE (DEGREES)
2/2/84
CED

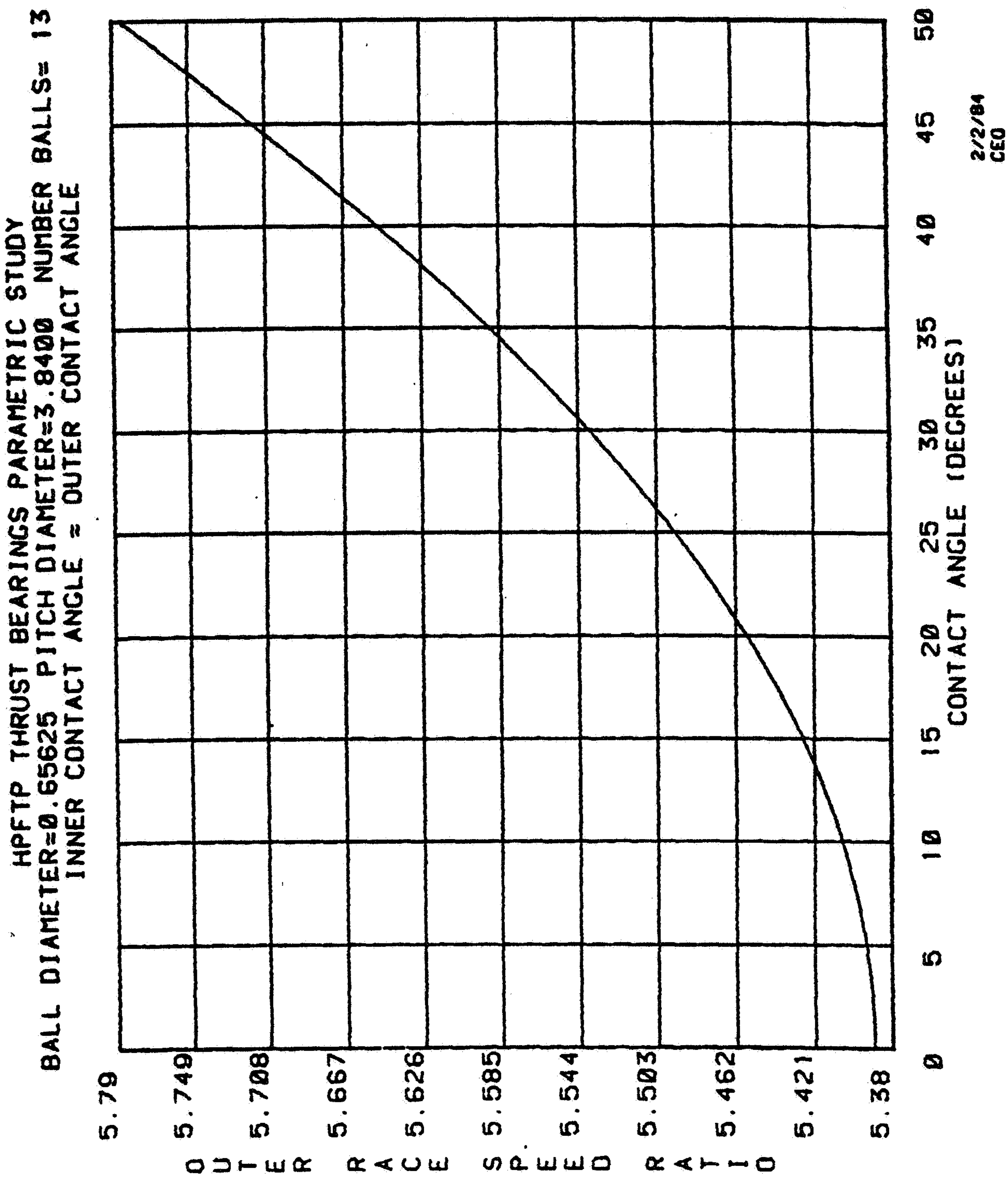

HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
6.34
6.303
6.266
6.229
6.192
6.155
6.118
6.081
6.044
6.007
5.97
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CED


HPFTP PUMP & TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.34375 PITCH DIAMETER=2.3400 NUMBER BALLS= 14
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
INNER RACE SPEED RATIO
8.03
7.993
7.956
7.919
7.882
7.845
7.808
7.771
7.734
7.697
7.66
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CED



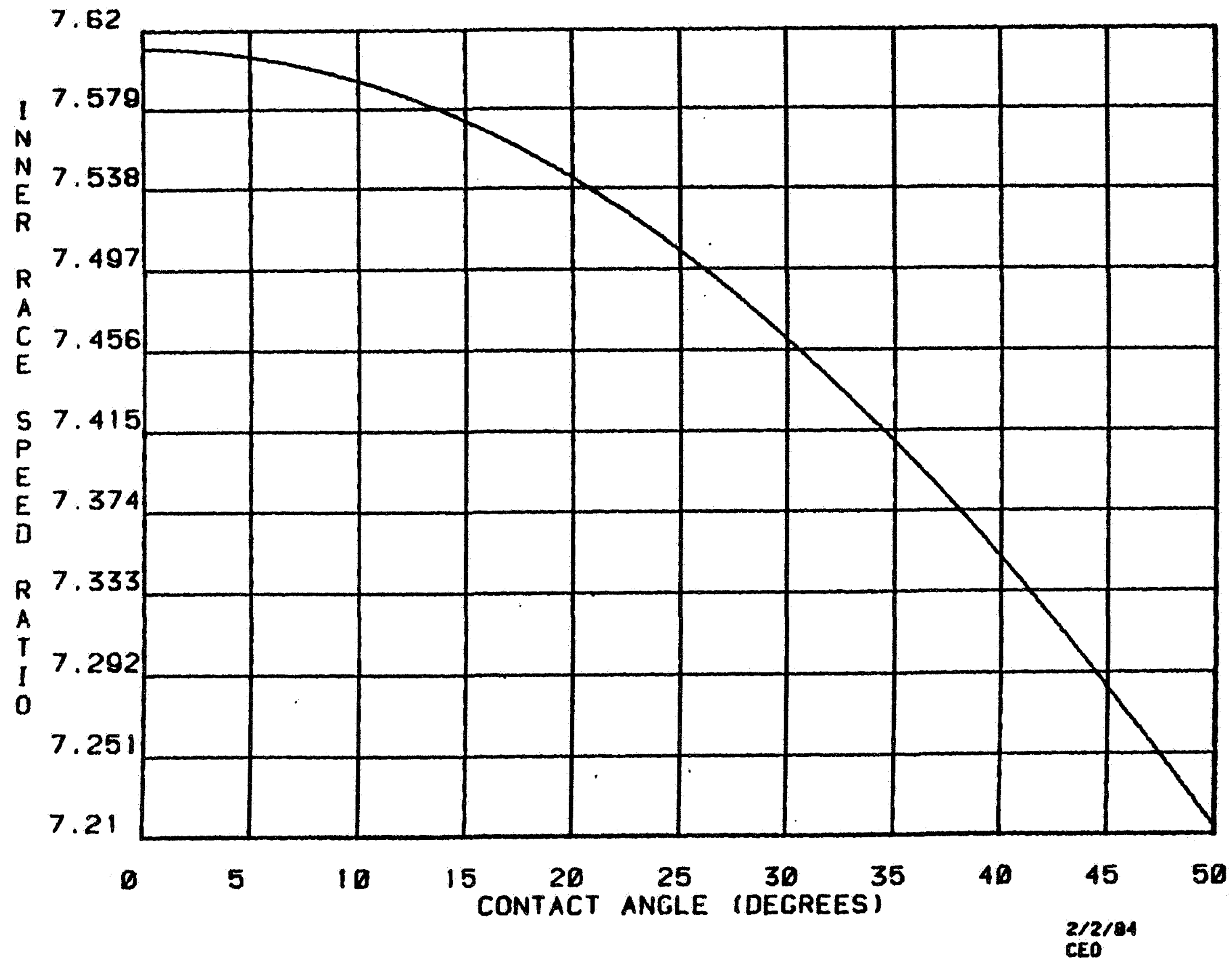
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.446
0.4428
0.4396
0.4364
0.4332
0.43
0.4268
0.4236
0.4204
0.4172
0.414
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CEO

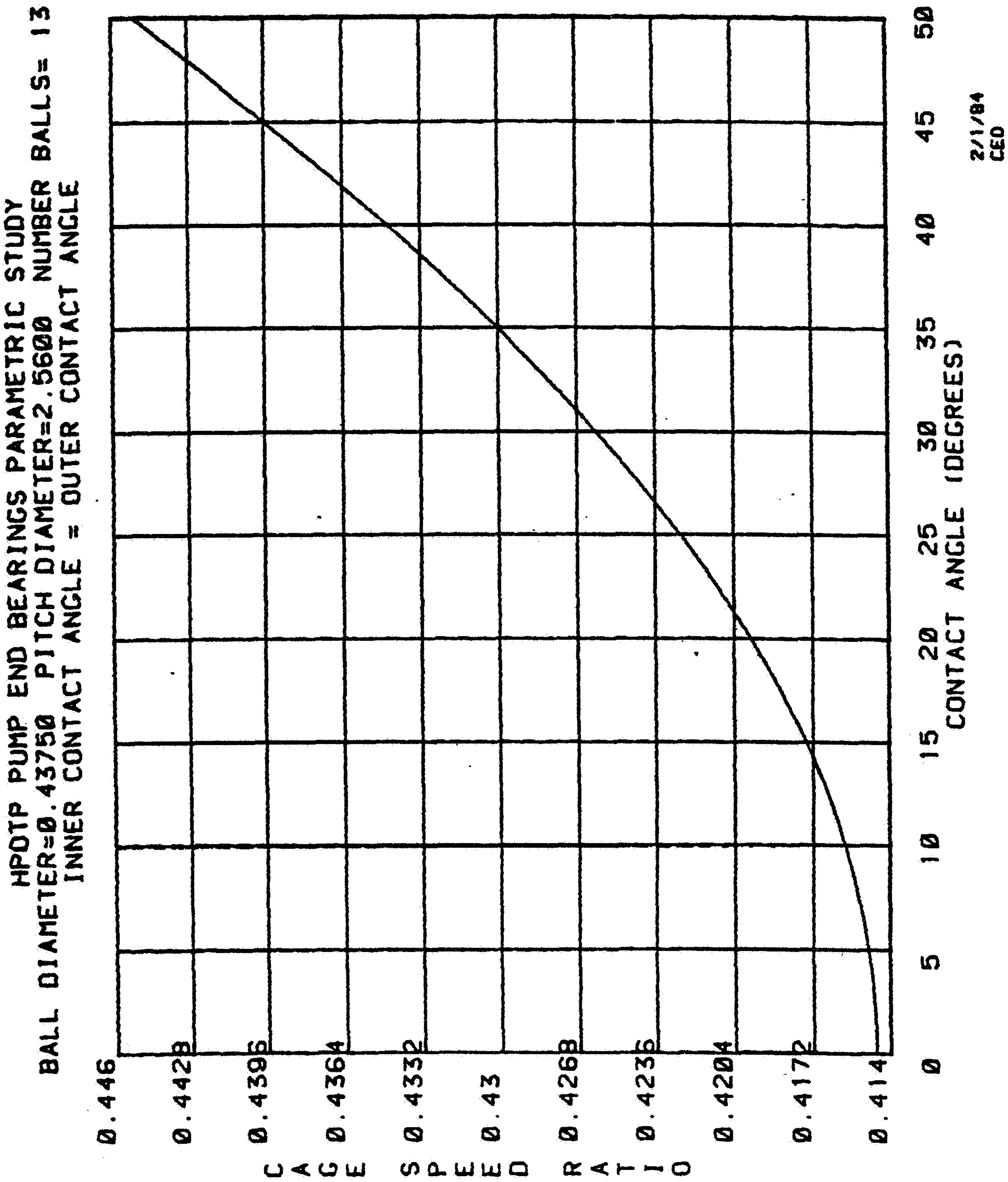

HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
2.9
2.894
2.888
2.882
2.876
2.87
2.864
2.858
2.852
2.846
2.84
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CEO

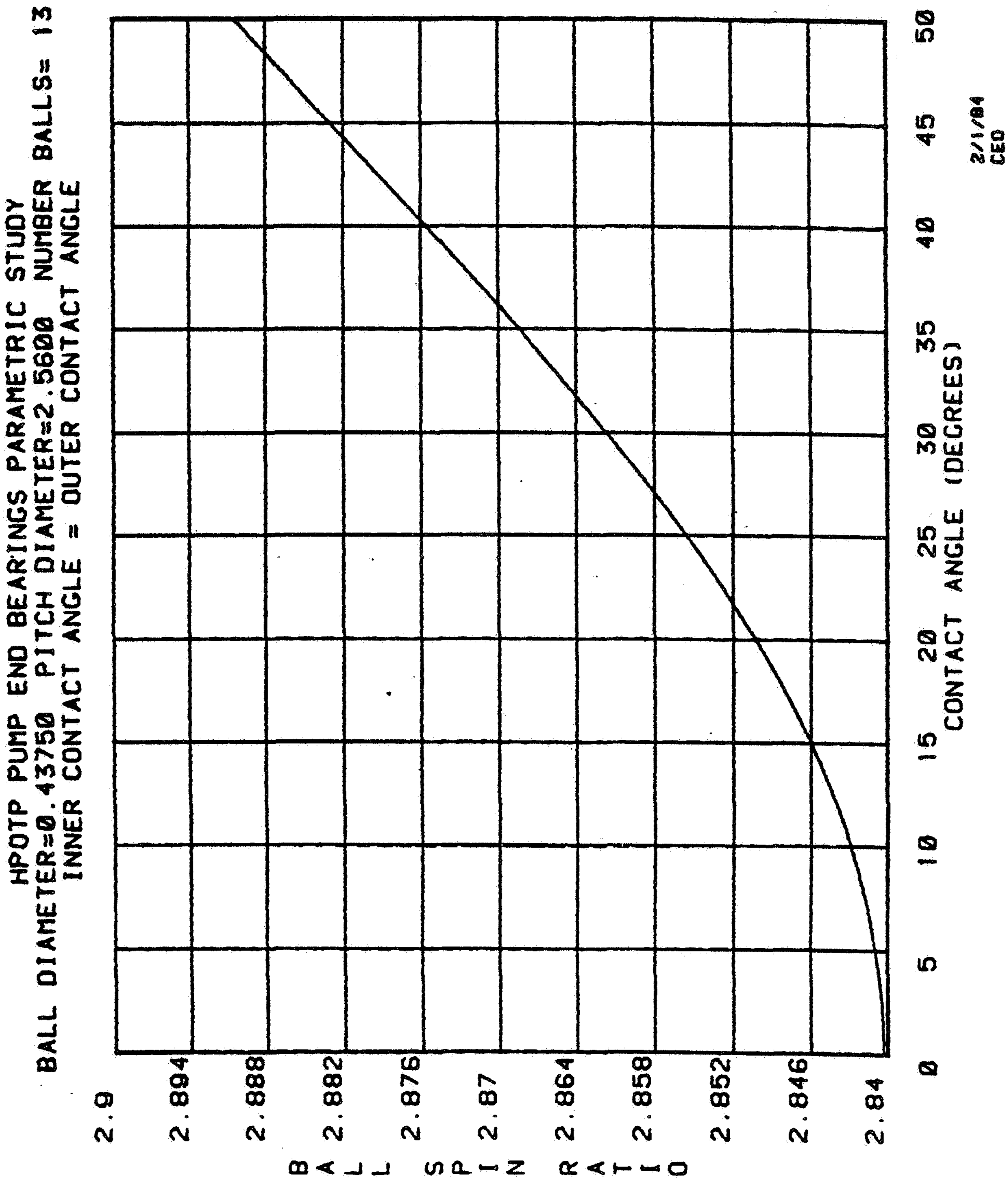


HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
5.79
5.749
5.708
5.667
5.626
5.585
5.544
5.503
5.462
5.421
5.38
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/2/84
CEO

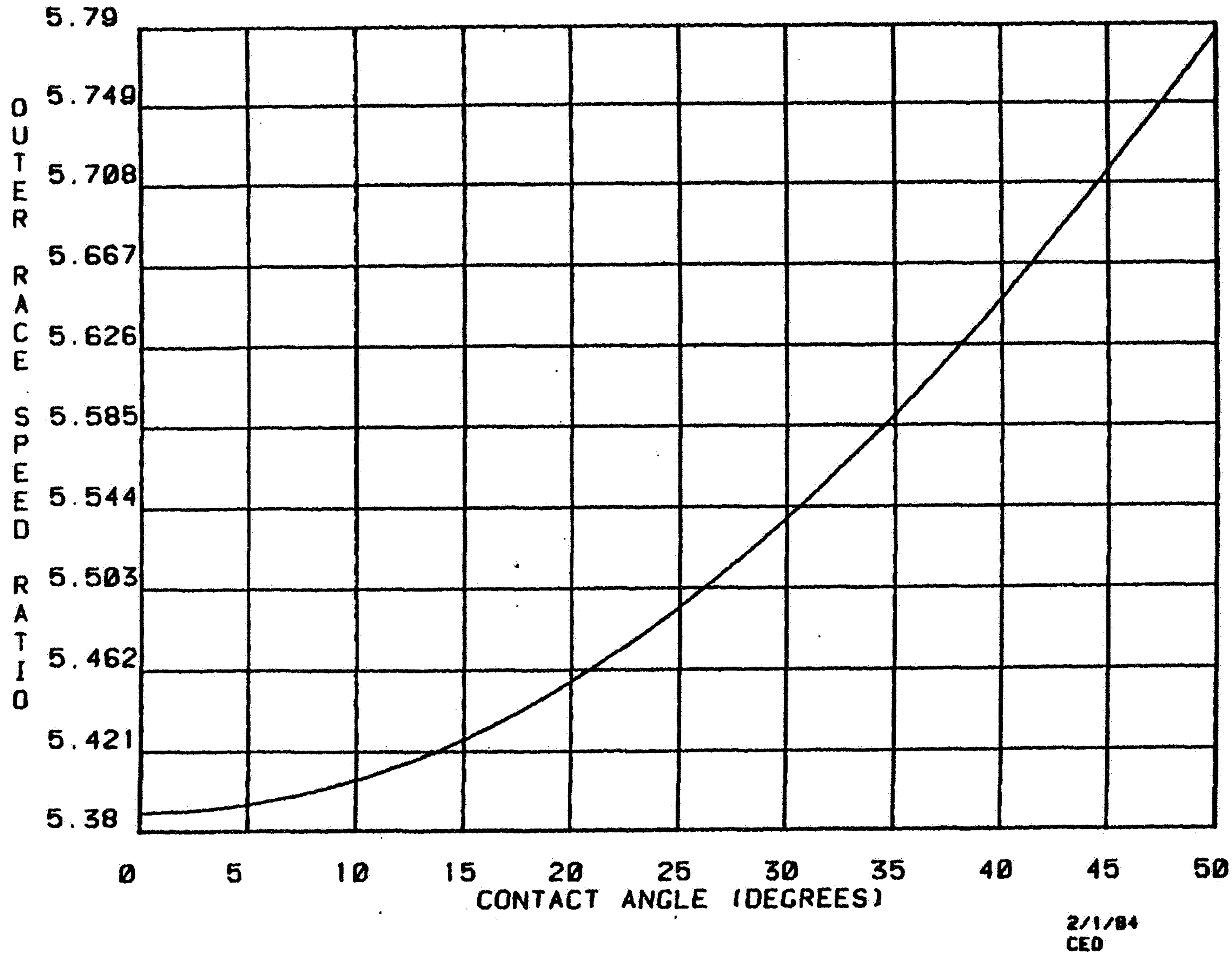
HPFTP THRUST BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.65625 PITCH DIAMETER=3.8400 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE

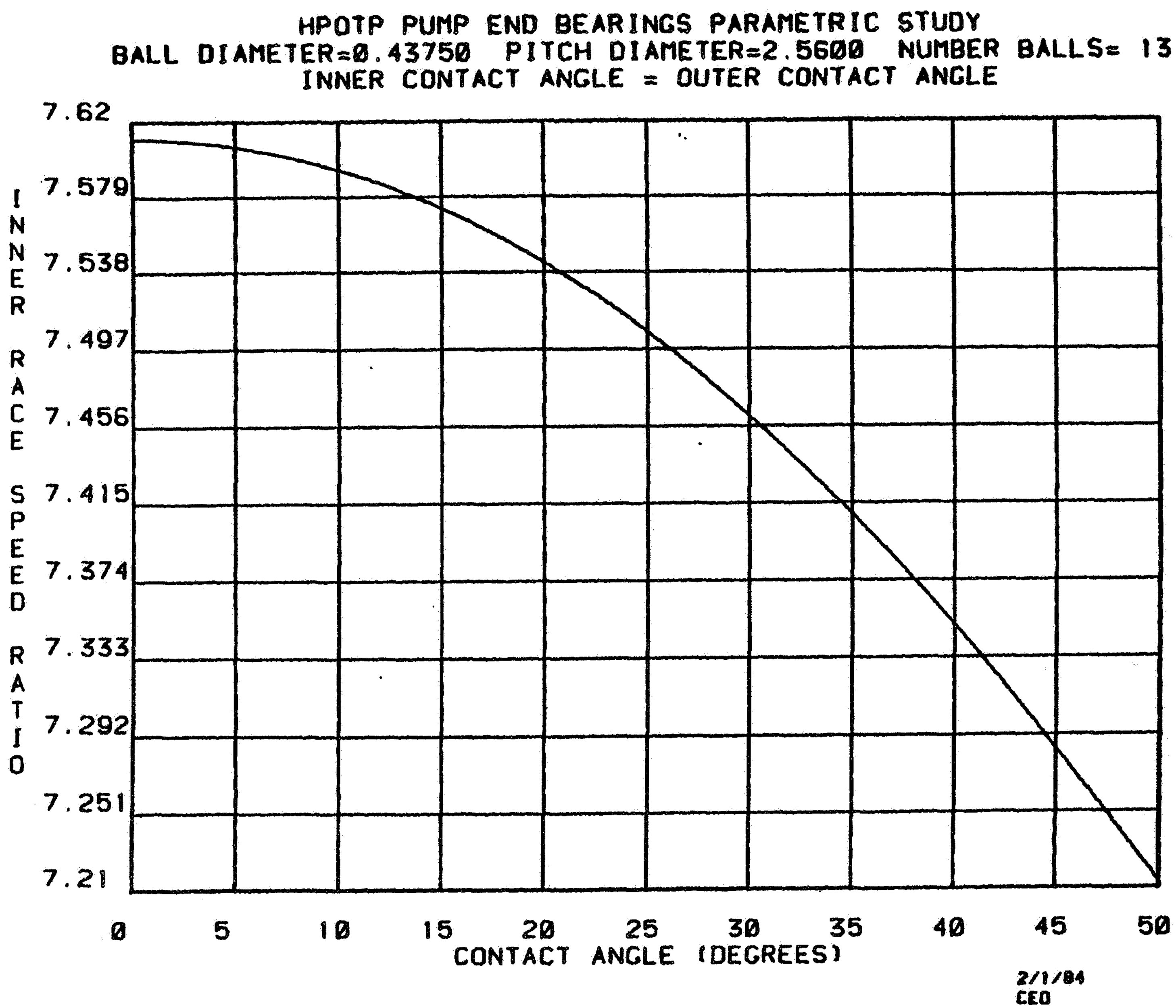


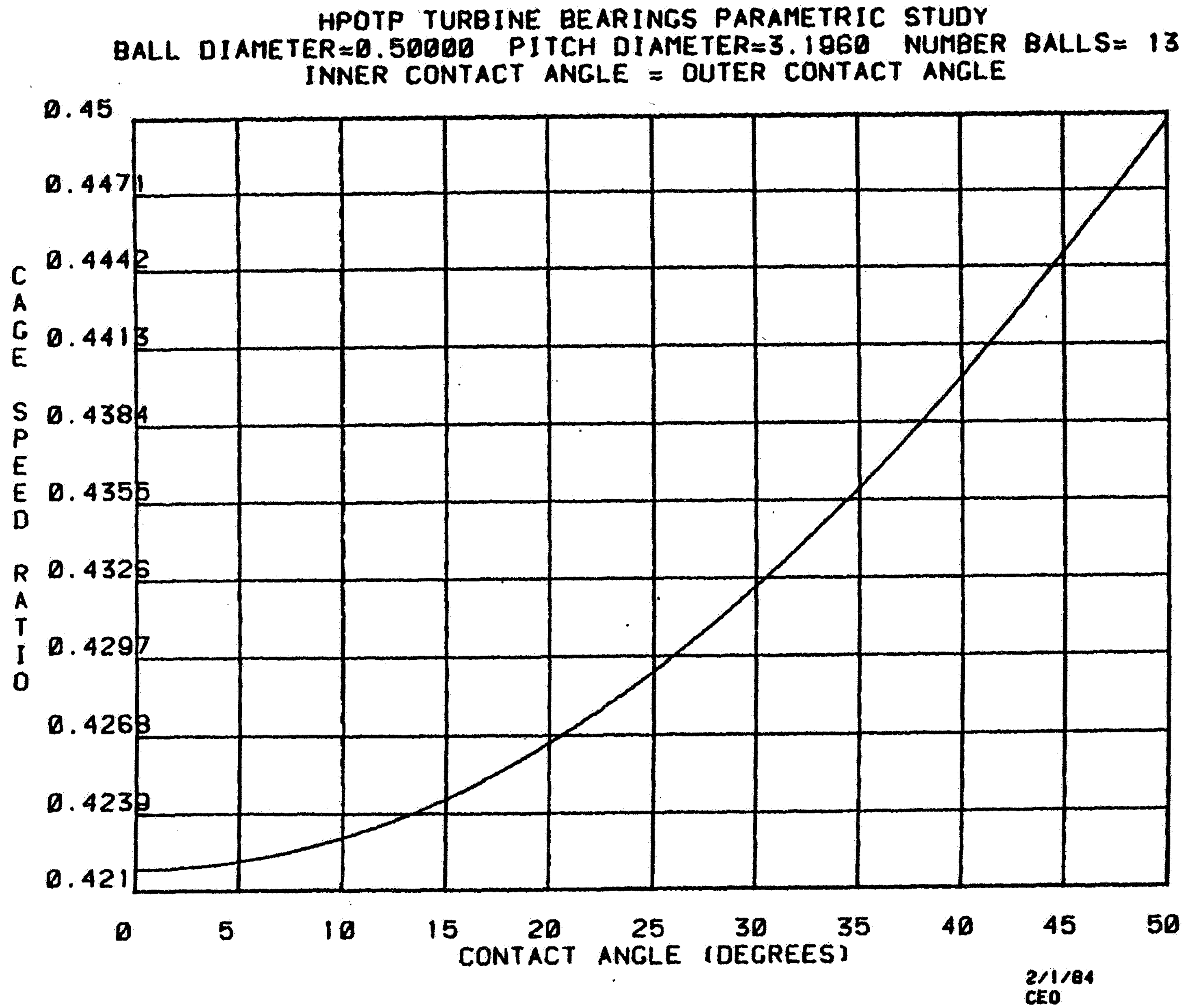

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.446
0.4428
0.4396
0.4364
0.4332
0.43
0.4268
0.4236
0.4204
0.4172
0.414
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED


HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
2.9
2.894
2.888
2.882
2.876
2.87
2.864
2.858
2.852
2.846
2.84
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED

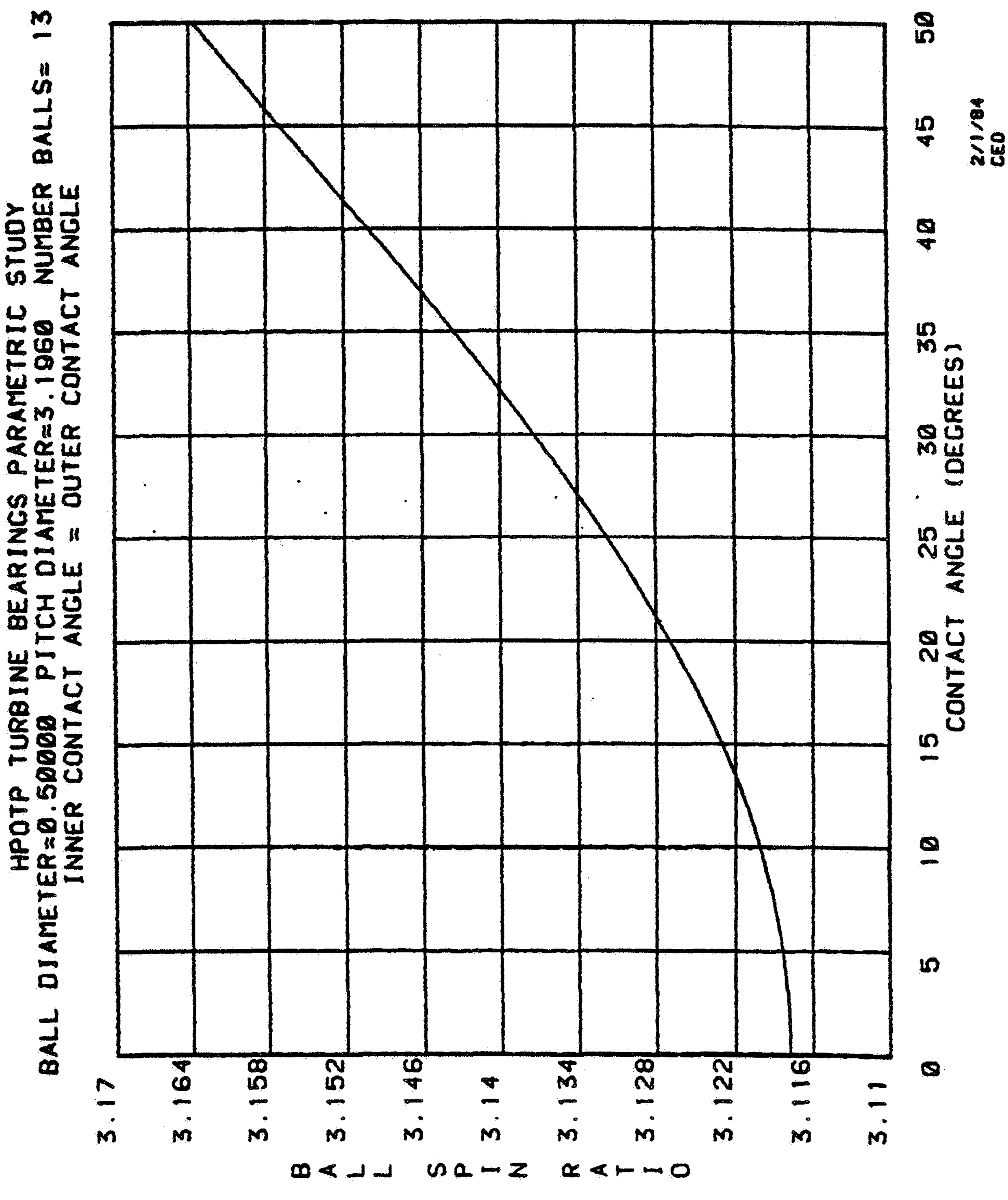
HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE

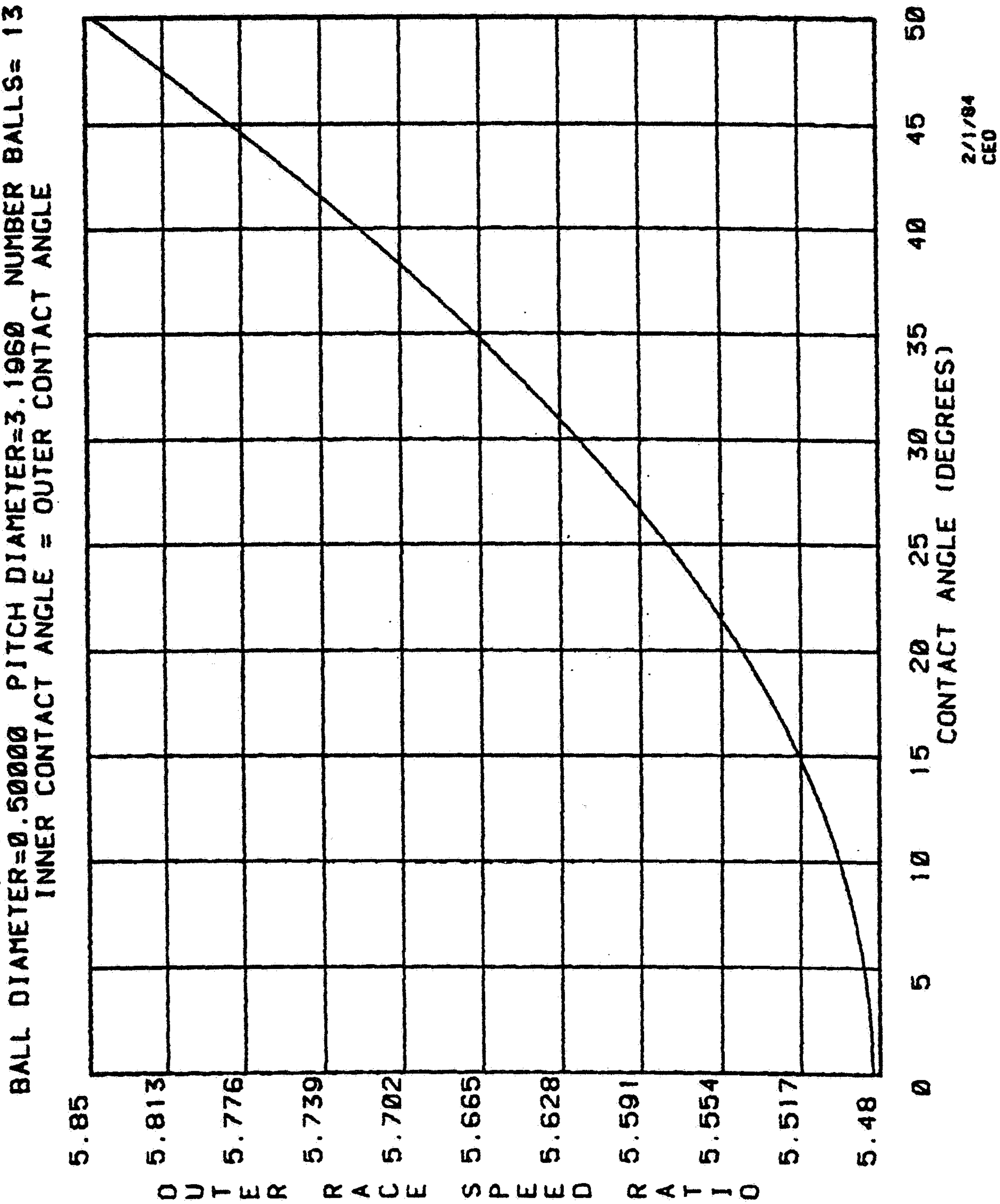


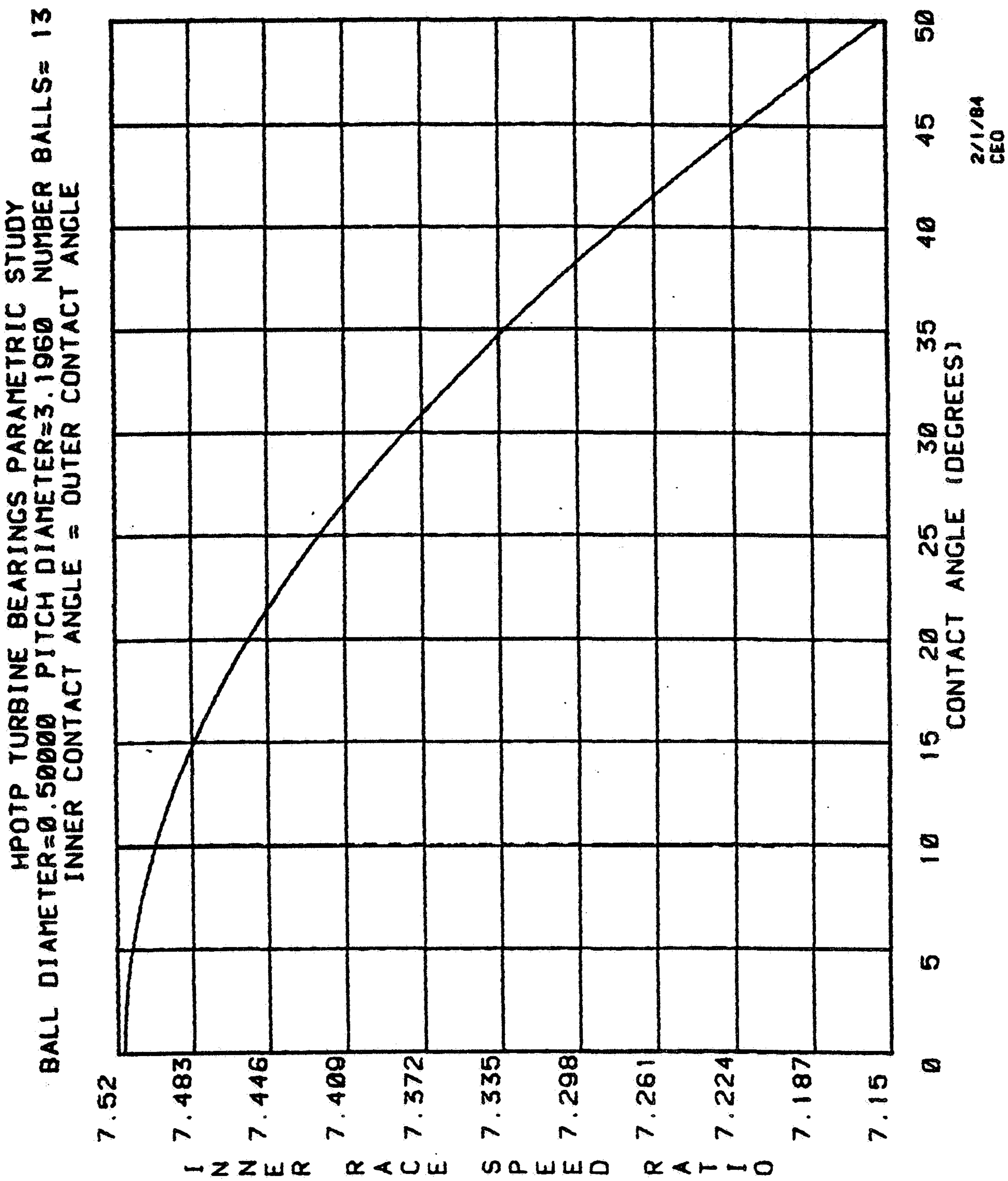

HPOTP PUMP END BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.43750 PITCH DIAMETER=2.5600 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
INNER RACE SPEED RATIO
7.62
7.579
7.538
7.497
7.456
7.415
7.374
7.333
7.292
7.251
7.21
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO



HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
CAGE SPEED RATIO
0.45
0.4471
0.4442
0.4413
0.4384
0.4355
0.4326
0.4297
0.4268
0.4239
0.421
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
BALL SPIN RATIO
3.17
3.164
3.158
3.152
3.146
3.14
3.134
3.128
3.122
3.116
3.11
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CED


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.19600 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
OUTER RACE SPEED RATIO
5.85
5.813
5.776
5.739
5.702
5.665
5.628
5.591
5.554
5.517
5.48
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER CONTACT ANGLE = OUTER CONTACT ANGLE
INNER RACE SPEED RATIO
7.52
7.483
7.446
7.409
7.372
7.335
7.298
7.261
7.224
7.187
7.15
0
5
10
15
20
25
30
35
40
45
50
CONTACT ANGLE (DEGREES)
2/1/84
CEO

COMPUTER PROGRAM LISTING

HOW TO USE PROGRAM TO PLOT EQUATIONS

UDK 2 LISTS THESE PARAMETERS

```
1310 REM ****************************************************
1320 REM ****************************************************
1330 REM ****************************************************
1340 REM    A1 = INNER RACE CONTACT ANGLE
1350 REM    B1 = BALL DIAMETER
1360 REM    P1 = PITCH DIAMETER
1370 REM    N1 = NUMBER OF BALLS
1380 A1=3
1390 B1=0.65625
1400 P1=3.84
1410 N1=13
1420 A$="HPFTP THRUST BEARINGS PARAMETRIC STUDY"
1430 B$="INNER CONTACT ANGLE = OUTER CONTACT ANGLE"
1440 C$="INNER RACE CONTACT ANGLE = "
1450 X$="OUTER RACE CONTACT ANGLE (DEGREES)"
1460 PRINT @32,21:100,5
1470 CHARSIZE 2
1480 PRINT "2/13/84"
1490 PRINT @32,21:100,3
1500 PRINT "CEO"
1510 SET DEGREES
1520 CHARSIZE 3
1530 REM ****************************************************
1540 REM ****************************************************
1550 REM ****************************************************
```

PUT CORRECT DATE & INITIALS

```
1390
1390 B1=0.88888
1400
1400 P1=3.886
1420
1420 A$="HPBTP [illegible] BEARINGS PARAMETRIC STUDY"
1420 A$="HPOTP TURBINE                    BEARINGS PARAMETRIC STUDY"
1420 A$="HPOTP TURBINE BEARINGS PARAMETRIC STUDY"
```

CHANGE PARAMETERS TO CORRECT VALUES USING PROGRAM EDITOR

UDK 2 AGAIN TO CHECK

```
1310 REM **************************************************
1320 REM **************************************************
1330 REM **************************************************
1340 REM     A1 = INNER RACE CONTACT ANGLE
1350 REM     B1 = BALL DIAMETER
1360 REM     P1 = PITCH DIAMETER
1370 REM     N1 = NUMBER OF BALLS
1380 A1=3
1390 B1=0.5
1400 P1=3.196
1410 N1=13
1420 A$="HPOTP TURBINE BEARINGS PARAMETRIC STUDY"
1430 B$="INNER CONTACT ANGLE = OUTER CONTACT ANGLE"
1440 C$="INNER RACE CONTACT ANGLE = "
1450 X$="OUTER RACE CONTACT ANGLE (DEGREES)"
1460 PRINT @32,21:100,5
1470 CHARSIZE 2
1480 PRINT "2/13/84"
1490 PRINT @32,21:100,3
1500 PRINT "CEO"
1510 SET DEGREES
1520 CHARSIZE 3
1530 REM **************************************************
1540 REM **************************************************
1550 REM **************************************************
```

UDK 1 GIVES THIS MENU

```
INNER CONTACT ANGLE = OUTER CONTACT ANGLE

1.....CAGE SPEED RATIO
2.....INNER RACE SPEED RATIO
3.....OUTER RACE SPEED RATIO
4.....BALL SPIN RATIO

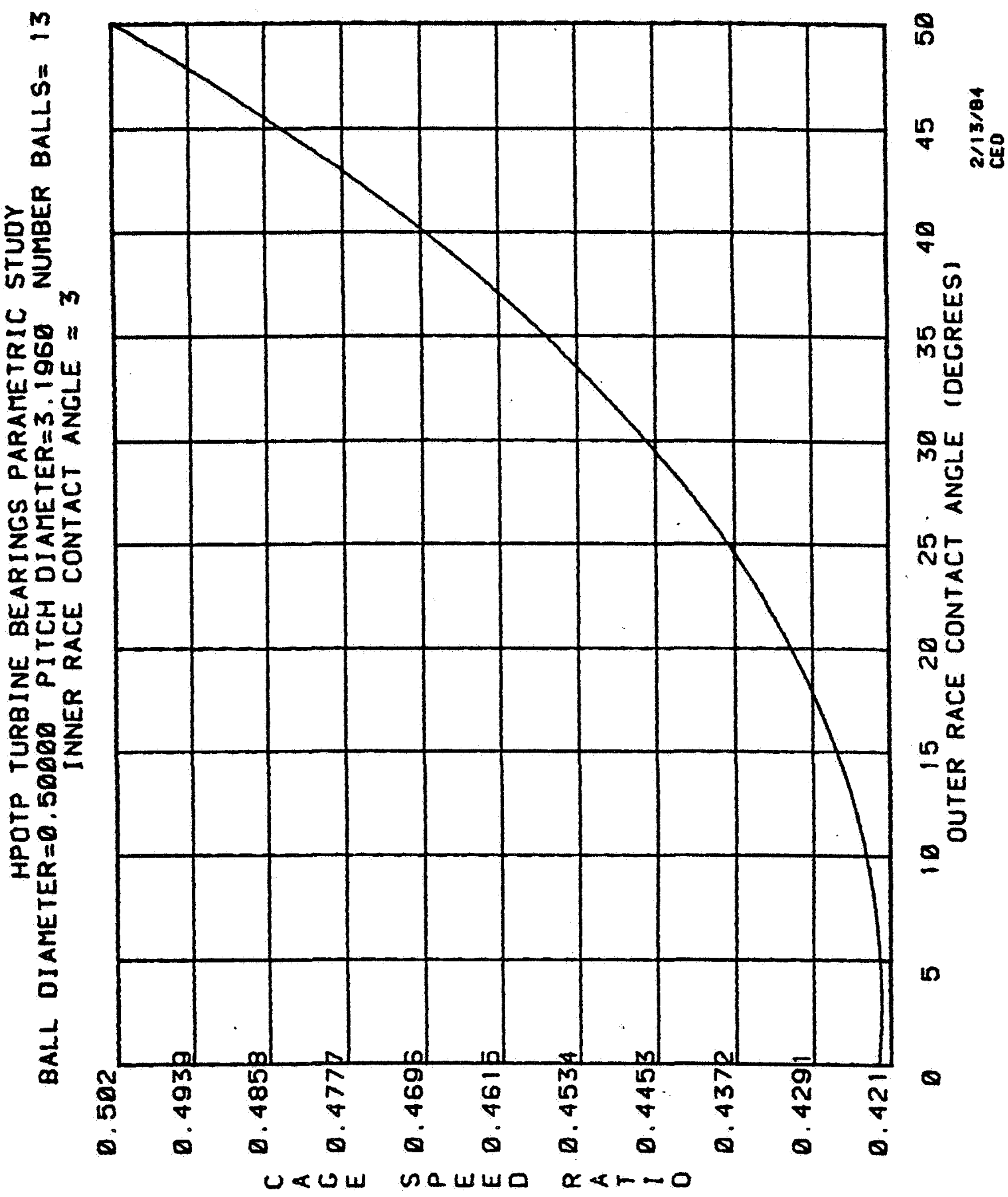
INNER CONTACT ANGLE = A CONSTANT

5.....CAGE SPEED RATIO
6.....INNER RACE SPEED RATIO
7.....OUTER RACE SPEED RATIO
8.....BALL SPIN RATIO
5
```

ENTER 1-8 AND HIT RETURN.
THE PROGRAM WILL PLOT THE
EQUATION YOU CHOOSE.

```
***************
* AUTORANGING *
***************
```

2/13/84
CEO


HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13
INNER RACE CONTACT ANGLE = 3
OUTER RACE CONTACT ANGLE (DEGREES)
0 5 10 15 20 25 30 35 40 45 50
CAGE SPEED RATIO
0.502 0.4939 0.4858 0.4777 0.4696 0.4615 0.4534 0.4453 0.4372 0.4291 0.421
2/13/84
CED

```
4 REM CHOOSE & PLOT EQN <<<<< UDK 1 >>>>>
5 GO TO 220
8 REM LIST PARAMETERS <<<<< UDK 2 >>>>>
9 PAGE
10 LIST 1310,1550
11 END
100 REM ******** LIST OF VARIABLES *********
110 REM   K(6).....WINDOW & GRID INCREMENTS
120 REM   A$,B$,C$......TITLES
130 REM   X$,Y$......X & Y AXIS LABELS
140 REM   A1.....INNER CONTACT ANGLE
150 REM   B1.....BALL DIAMETER
160 REM   P1.....PITCH DIAMETER
170 REM   N1.....NUMBER OF BALLS
180 REM   X.....X COORDINATE FOR PLOTS (OUTER CONTACT ANGLE)
190 REM   Y.....COMPUTED Y COORDINATE
200 REM   Y1,Y2,Y3,Y4.....USED IN AUTORANGING
210 REM   I,J,L,O$.....LOOP COUNTERS & GENERAL REGISTERS
220 REM ****** CHOOSE EQUATION *****
230 PAGE
240 PRINT "JINNER CONTACT ANGLE = OUTER CONTACT ANGLEJ"
250 PRINT "1.....CAGE SPEED RATIO"
260 PRINT "2.....INNER RACE SPEED RATIO"
270 PRINT "3.....OUTER RACE SPEED RATIO"
280 PRINT "4.....BALL SPIN RATIO"
290 PRINT "JINNER CONTACT ANGLE = A CONSTANTJ"
300 PRINT "5.....CAGE SPEED RATIO"
310 PRINT "6.....INNER RACE SPEED RATIO"
320 PRINT "7.....OUTER RACE SPEED RATIO"
330 PRINT "8.....BALL SPIN RATIO"
340 INPUT Z
350 IF Z>0 AND Z<9 THEN 380
360 PRINT "G"
370 GO TO 220
380 DIM K(6)
390 K(1)=0
400 K(2)=50
410 K(3)=0
420 K(4)=10
430 REM **** AUTORANGE *******
440 PAGE
450 PRINT @32,21:53,50
460 PRINT "**************HHHHHHHHHHHHHHHJ* AUTORANGING *";
470 PRINT "HHHHHHHHHHHHHHHJ***************"
480 GOSUB 1300
490 Y3=INT(LGT(Y1))
500 Y4=INT(LGT(Y2))
510 K(3)=INT(Y1/10↑(Y3-2))*10↑(Y3-2)
520 K(4)=(INT(Y2/10↑(Y4-2))+1)*10↑(Y4-2)
530 REM *** WRITING HEADINGS ***
540 PAGE
550 WINDOW 0,130,0,100
560 VIEWPORT 15,113,15,90
570 AXIS 0,0,130,100
580 AXIS 130,100
590 REM *** TITLE ***
600 MOVE 65,111
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
610 FOR I=1 TO LEN(A$)/2
620 PRINT "H";
630 NEXT I
640 PRINT A$
650 MOVE 65,104
660 GO TO Z OF 670,670,670,670,720,720,720,720
670 FOR I=1 TO LEN(B$)/2
680 PRINT "H";
690 NEXT I
700 PRINT B$
710 GO TO 760
720 FOR I=1 TO LEN(C$)/2
730 PRINT "H";
740 NEXT I
750 PRINT C$;A1
760 MOVE -2,107.5
770 PRINT USING 780:B1,P1,"  NUMBER BALLS=",N1
780 IMAGE "BALL DIAMETER=",1D.5D,"  PITCH DIAMETER=",1D.4D,15A,3D
790 REM ******* VERTICAL LABEL*******
800 K3=LEN(Y$)
810 MOVE 0,50
820 PRINT "HHHHHHH";
830 FOR I=1 TO K3/2
840 PRINT "K";
850 NEXT I
860 DELETE O$
870 DIM O$(1)
880 FOR I=1 TO K3
890 O$=SEG(Y$,I,1)
900 PRINT O$;"HJ";
910 NEXT I
920 REM *******HORIZONTAL LABEL*****
930 MOVE 65,0
940 PRINT "JJJ";
950 FOR I=1 TO LEN(X$)/2
960 PRINT "H";
970 NEXT I
980 PRINT X$
990 HOME
1000 WINDOW K(1),K(2),K(3),K(4)
1010 K(5)=(K(2)-K(1))/10
1020 K(6)=(K(4)-K(3))/10
1030 AXIS K(5),K(6),K(1),K(3)
1040 REM *** LABELING TIC MARKS ***
1050 FOR I=0 TO 10 STEP 1
1060 MOVE K(1)+I*K(5),K(3)
1070 PRINT "JJH";I*K(5)+K(1)
1080 NEXT I
1090 FOR I=0 TO 10 STEP 1
1100 MOVE K(1),I*K(6)+K(3)
1110 PRINT "HHHHH";I*K(6)+K(3)
1120 NEXT I
1130 GOSUB 1160
1140 GOSUB 1300
1150 RETURN
1160 REM *** DRAWING GRID ***
1170 MOVE K(1),K(3)
1180 FOR I=K(1) TO K(2) STEP K(5)
```

```
1100 RMOVE K(5),0
1200 RDRAW 0,K(4)
1210 RMOVE 0,-K(4)
1220 NEXT I
1230 MOVE K(1),K(3)
1240 FOR I=K(3) TO K(4) STEP K(6)
1250 RMOVE 0,K(6)
1260 RDRAW K(2),0
1270 RMOVE -K(2),0
1280 NEXT I
1290 RETURN
1300 REM DRAW THE EQUATION
1310 REM **************************************************
1320 REM **************************************************
1330 REM **************************************************
1340 REM     A1 = INNER RACE CONTACT ANGLE
1350 REM     B1 = BALL DIAMETER
1360 REM     P1 = PITCH DIAMETER
1370 REM     N1 = NUMBER OF BALLS
1380 A1=3
1390 B1=0.5
1400 P1=3.196
1410 N1=13
1420 A$="HPOTP TURBINE BEARINGS PARAMETRIC STUDY"
1430 B$="INNER CONTACT ANGLE = OUTER CONTACT ANGLE"
1440 C$="INNER RACE CONTACT ANGLE = "
1450 X$="OUTER RACE CONTACT ANGLE (DEGREES)"
1460 PRINT @32,21:100,5
1470 CHARSIZE 2
1480 PRINT "x/xx/xx"
1490 PRINT @32,21:100,3
1500 PRINT "xxx"
1510 SET DEGREES
1520 CHARSIZE 3
1530 REM **************************************************
1540 REM **************************************************
1550 REM **************************************************
1560 X=K(1)
1570 GOSUB Z OF 1710,1750,1790,1830,1880,1920,1960,2000
1580 Y1=Y
1590 Y2=Y
1600 MOVE X,Y
1610 FOR X=K(1) TO K(2) STEP (K(2)-K(1))/500
1620 GOSUB Z OF 1710,1750,1790,1830,1880,1920,1960,2000
1630 IF Y>Y1 THEN 1650
1640 Y1=Y
1650 IF Y<Y2 THEN 1670
1660 Y2=Y
1670 DRAW X,Y
1680 NEXT X
1690 RETURN
1700 REM ********* INNER CONTACT ANGLE = OUTER CONTACT ANGLE *********
1710 REM COMPUTE VALUE
1720 Y$="CAGE SPEED RATIO"
1730 Y=0.5*(1-B1/P1*COS(X))
1740 RETURN
1750 REM COMPUTE VALUE
1760 Y$="INNER RACE SPEED RATIO"
```

```
1770 Y=N1/2*(1+B1/P1*COS(X))
1780 RETURN
1790 REM COMPUTE VALUE
1800 Y$="OUTER RACE SPEED RATIO"
1810 Y=N1/2*(1-B1/P1*COS(X))
1820 RETURN
1830 REM COMPUTE VALUE
1840 Y$="BALL SPIN RATIO"
1850 Y=P1/(2*B1)*(1-(B1/P1)↑2*COS(X)↑2)
1860 RETURN
1870 REM ********* INNER CONTACT ANGLE = A CONSTANT *********
1880 REM COMPUTE VALUE
1890 Y$="CAGE SPEED RATIO"
1900 Y=(1-COS(A1)*B1/P1)/(1+COS(A1-X))
1910 RETURN
1920 REM COMPUTE VALUE
1930 Y$="INNER RACE SPEED RATIO"
1940 Y=N1*(COS(A1-X)+COS(A1)*B1/P1)/(1+COS(A1-X))
1950 RETURN
1960 REM COMPUTE VALUE
1970 Y$="OUTER RACE SPEED RATIO"
1980 Y=N1*(1-COS(A1)*B1/P1)/(1+COS(A1-X))
1990 RETURN
2000 REM COMPUTE VALUE
2010 Y$="BALL SPIN RATIO"
2020 I=SIN(X)/(COS(X)+B1/P1)
2030 J=(COS(X)+I*SIN(X))/(1+COS(X)*B1/P1)
2040 L=(COS(A1)+I*SIN(A1))/(1-COS(A1)*B1/P1)
2050 Y=1/((J+L)*COS(ATN(I))*B1/P1)
2060 RETURN
10000 DATA 3,10,20,30
10010 DELETE A2
10020 DIM A2(4)
10030 RESTORE 10000
10040 READ A2
10050 FOR I1=1 TO 4
10060 A1=A2(I1)
10070 FOR Z=5 TO 8
10080 GOSUB 300
10085 COPY
10090 NEXT Z
10100 NEXT I1
10110 END
```

this loop can be used to automatically plot several equations

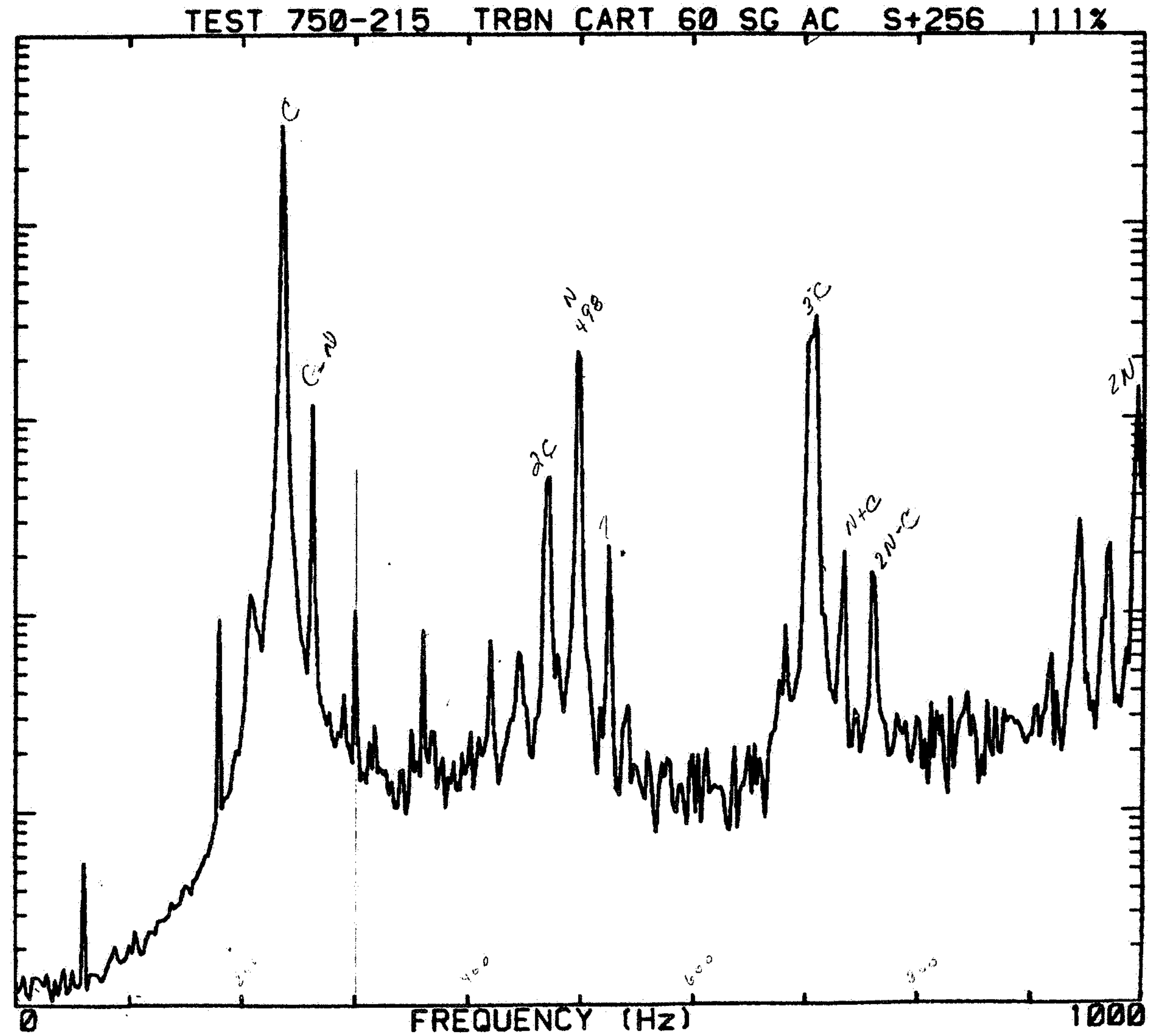
VALUES TO BE USED FOR INNER RACE CONTACT ANGLE

DIM TO SAME # OF POINTS IN DATA STATEMENT

CHOOSE WHICH EQUATIONS TO PLOT

INTERNALLY MEASURED BEARING FREQUENCIES OF TWO STATIC TEST FIRINGS

This section includes selected data in the form of working papers for two static firing tests, 750-215 and 750-234. The two major points of interest are the cage frequency on test 750-215 and the outer race frequency on test 750-234. Of special interest is the beating of the bearing frequencies with the synchronous frequency of the pump. The data in this section is only included to illustrate or demonstrate the applicability of the charts of the previous sections. A comparison of the measured frequency on test 750-234 and the applicable chart of the HPOTP outer race speed is also shown. Several points of possible contact angles for the measured speed ratio are shown on the chart. Also included is a plot of the outer race frequency for different power levels, including a slow ramp down. For this test, the contact angle does not appear to be a function of power level. When additional data from normal bearing operation, and especially from bearings that have experienced damage, becomes available, it is recommended that detailed analysis be performed and included in a report.

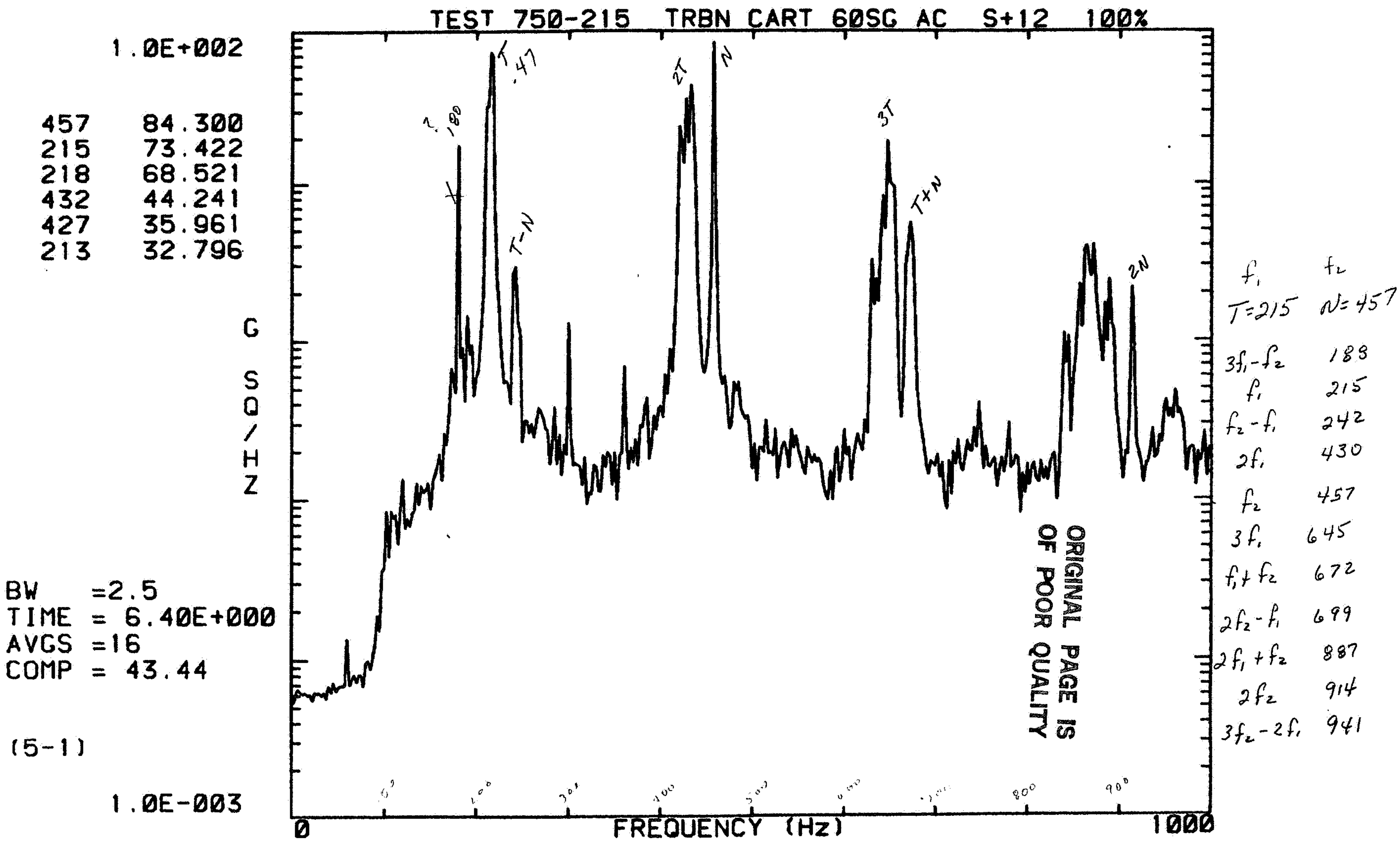


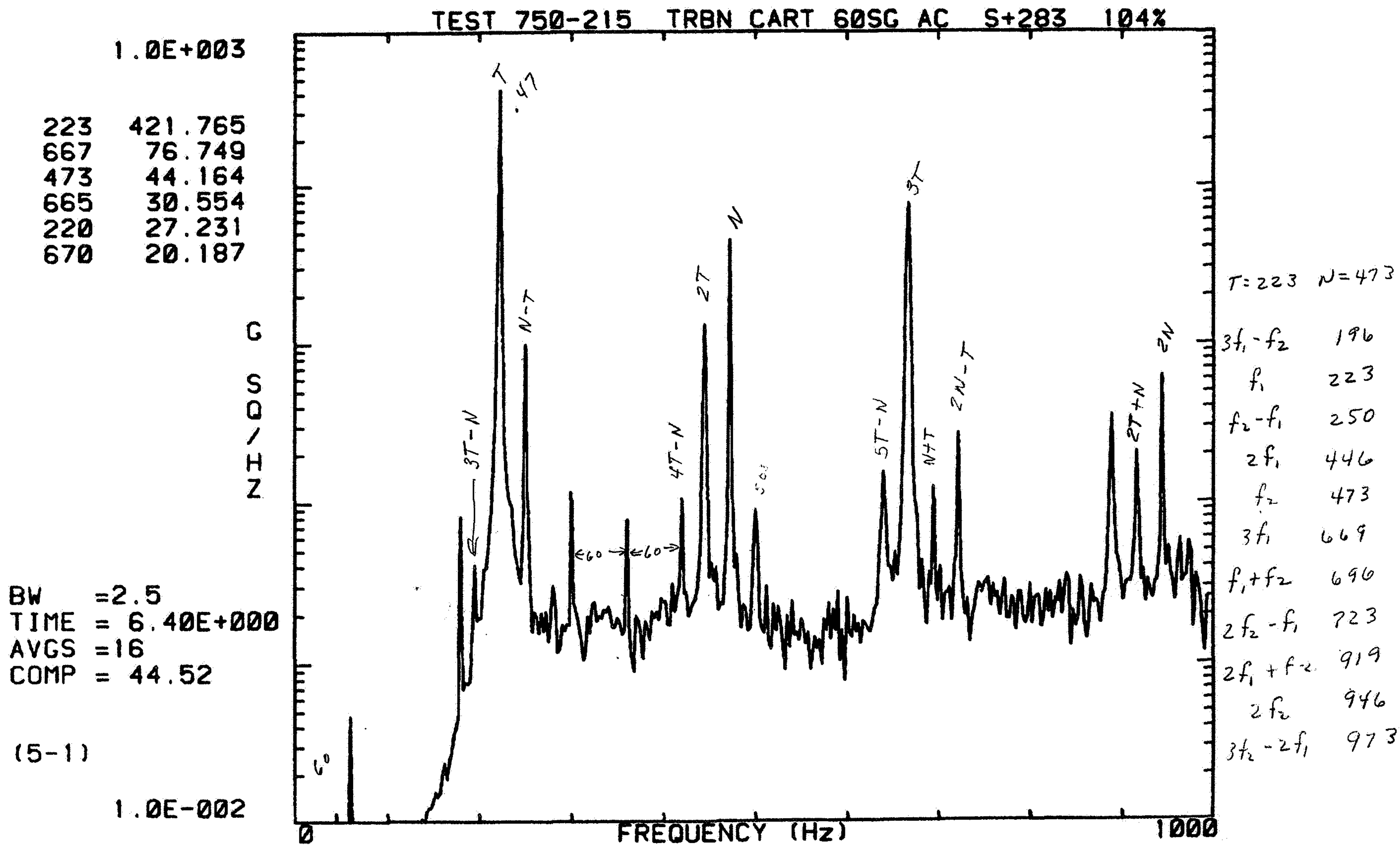
235	335.019
238	146.241
233	34.282
710	32.739
707	26.006
705	25.414

BW =2.5
TIME = 6.40E+000
AVGS =16
COMP = 46.95

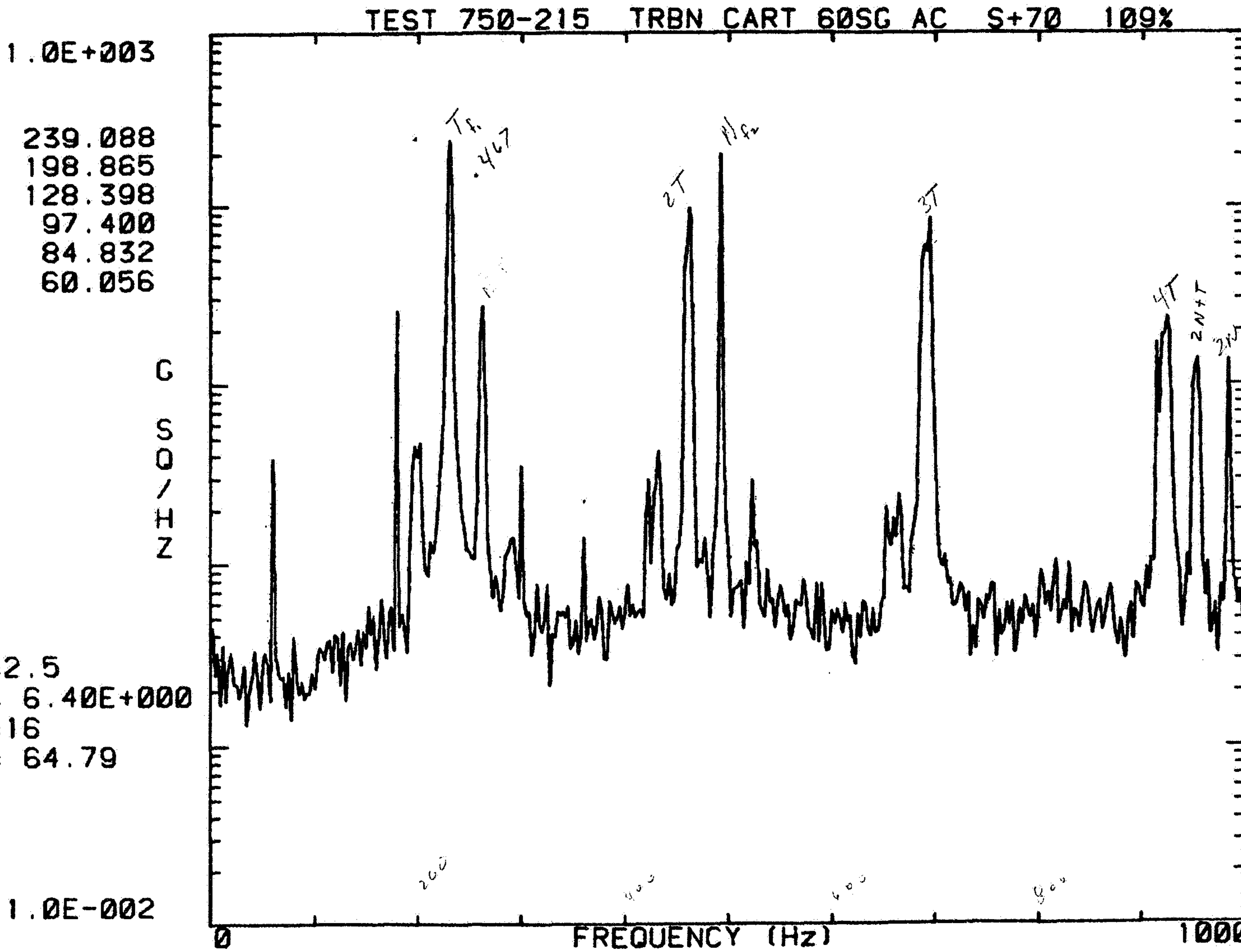
(5-1)

f_1	f_2
$C=235$	$N=497$
$3f_1-f_2$	208
f_1	235
f_2-f_1	262
$2f_1$	470
f_2	497
$3f_1$	705
f_1+f_2	732
$2f_2-f_1$	759
$2f_1+f_2$	967
$2f_2$	994
$3f_2-2f_1$	1021


TEST 750-215 TRBN CART 60SG AC S+12 100%
1.0E+002
457 84.300
215 73.422
218 68.521
432 44.241
427 35.961
213 32.796
G SQ/HZ
BW =2.5
TIME = 6.40E+000
AVGS =16
COMP = 43.44
(5-1)
1.0E-003
0
1000
FREQUENCY (Hz)
ORIGINAL PAGE IS OF POOR QUALITY
T
.47
2T
N
3T
T+N
T-N
2N
f_1 f_2
T=215 N=457
$3f_1-f_2$ 188
f_1 215
f_2-f_1 242
$2f_1$ 430
f_2 457
$3f_1$ 645
f_1+f_2 672
$2f_2-f_1$ 699
$2f_1+f_2$ 887
$2f_2$ 914
$3f_2-2f_1$ 941



TEST 750-215 TRBN CART 60SG AC S+283 104%
1.0E+003
223 421.765
667 76.749
473 44.164
665 30.554
220 27.231
670 20.187
G
SQ/HZ
BW =2.5
TIME = 6.40E+000
AVGS =16
COMP = 44.52
(5-1)
1.0E-002
0
FREQUENCY (Hz)
1000
T
.47
N-T
3T-N
←60→←60→
4T-N
2T
N
5T-N
3T
N+T
2N-T
2T+N
2N
T: 223 N=473
3f1 - f2 196
f1 223
f2 - f1 250
2f1 446
f2 473
3f1 669
f1 + f2 696
2f2 - f1 723
2f1 + f2 919
2f2 946
3f2 - 2f1 973



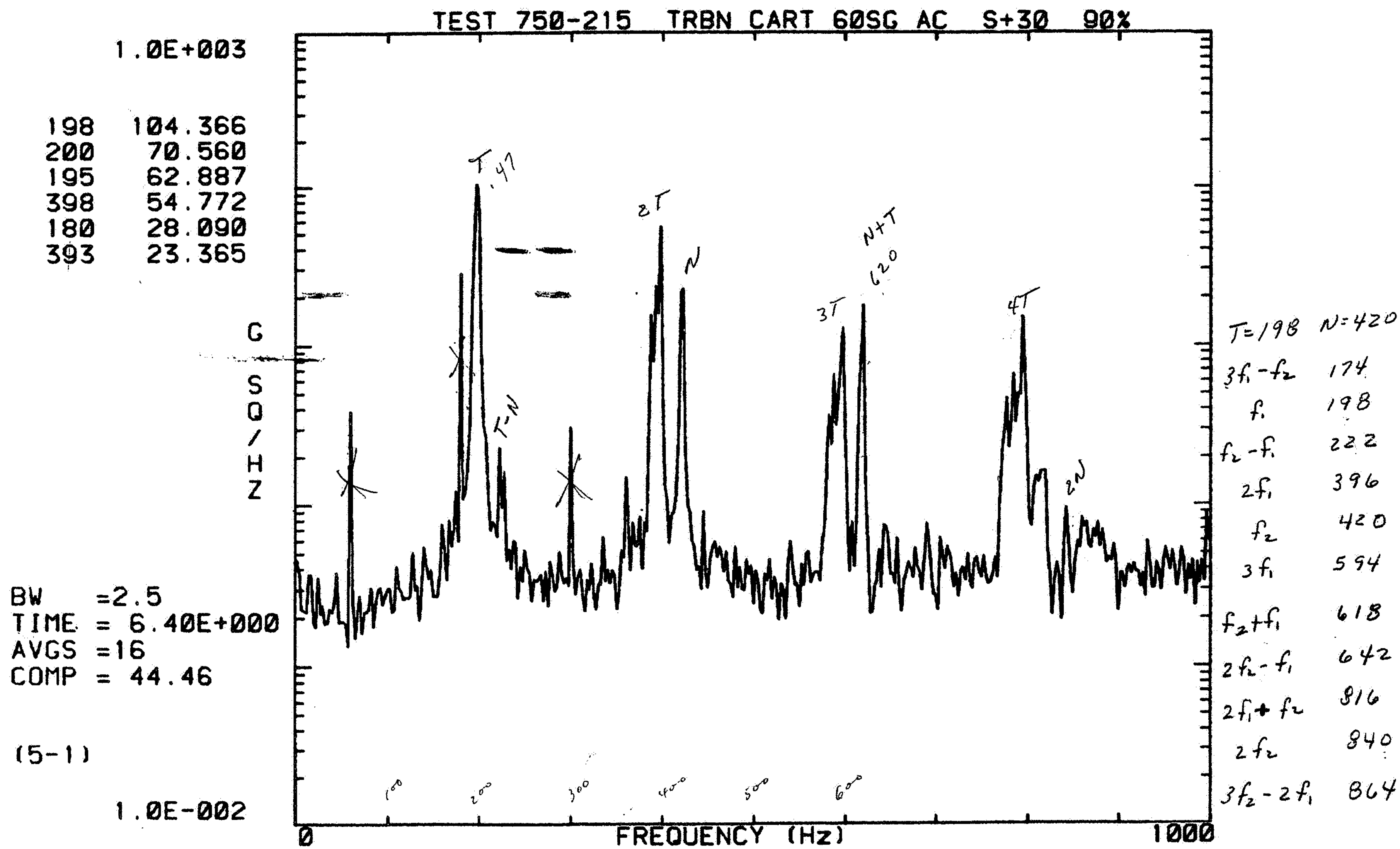
230	239.088
492	198.865
233	128.398
462	97.400
695	84.832
460	60.056

BW =2.5
TIME = 6.40E+000
AVGS =16
COMP = 64.79

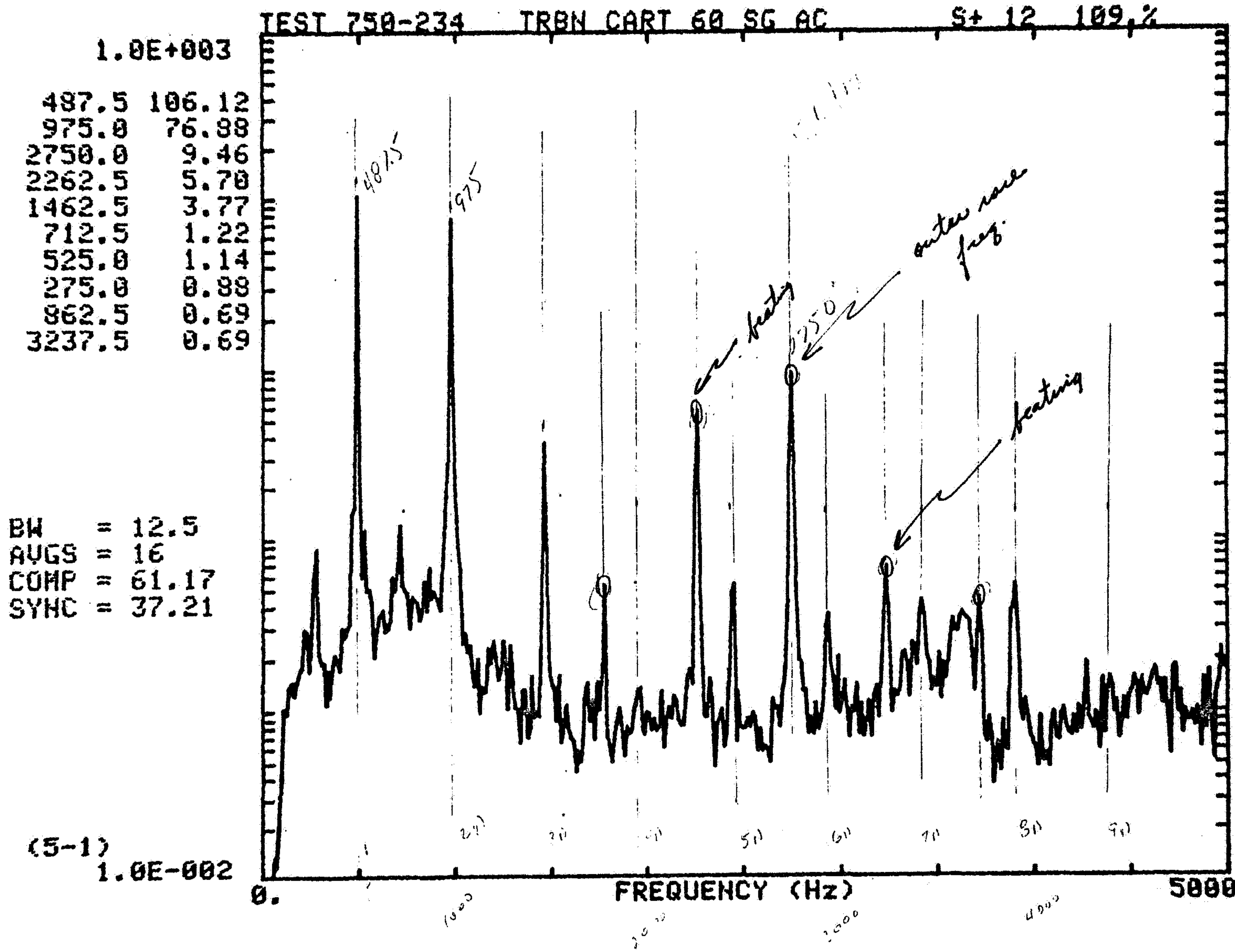
(5-1)

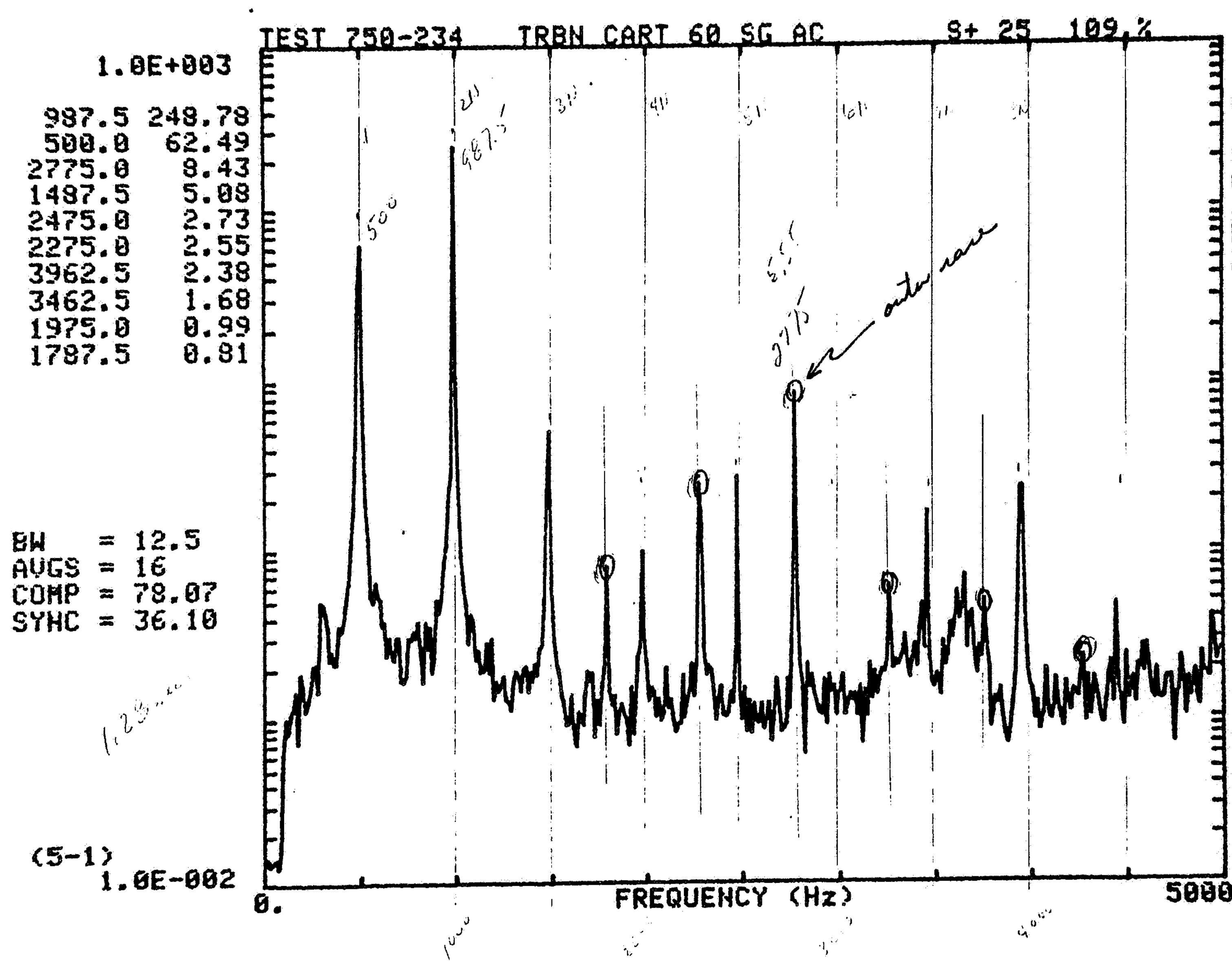
$T=230$ $N=492$

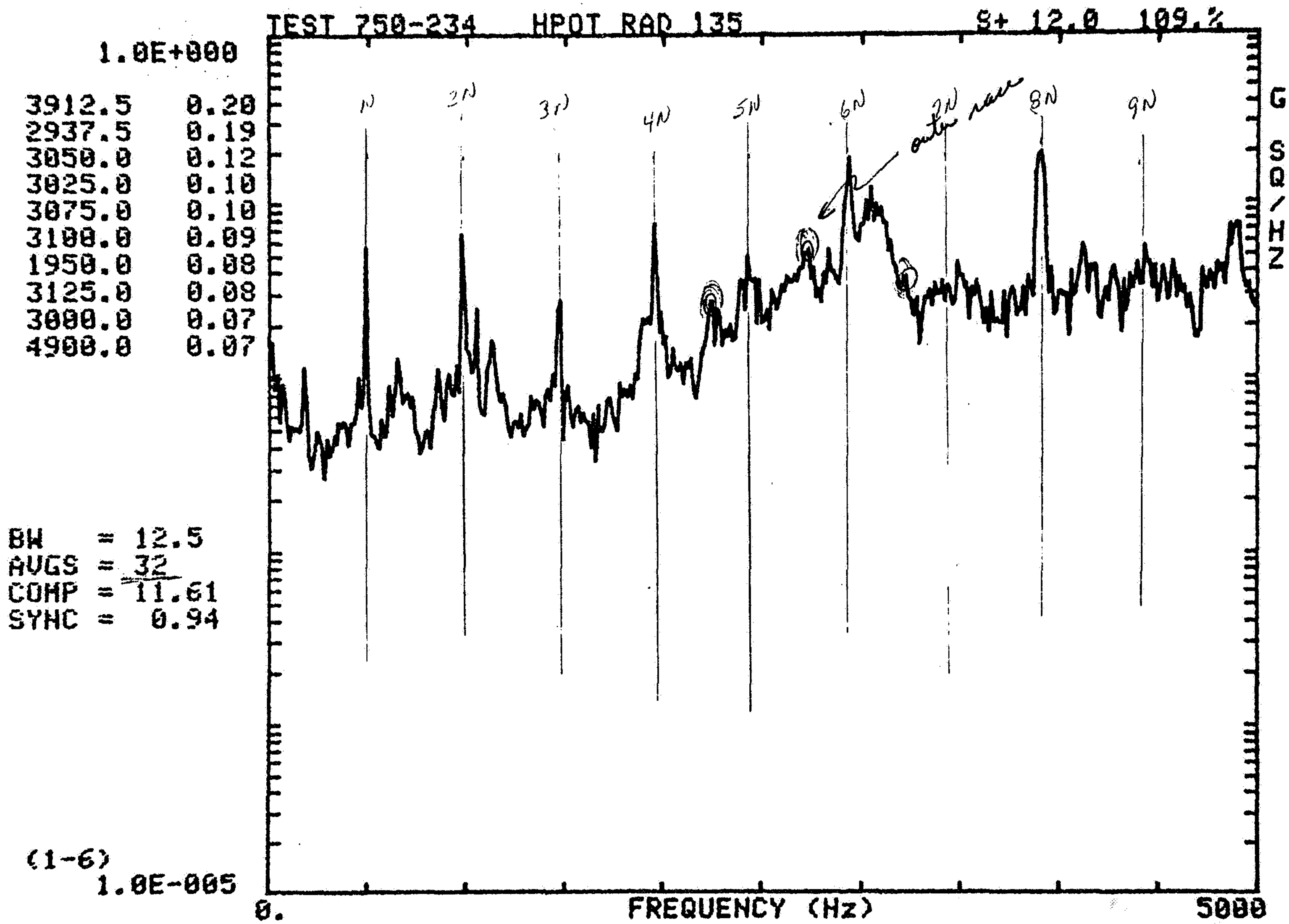
$3f_1-f_2$	198
f_1	230
f_2-f_1	262
$2f_1$	460
f_2	492
$3f_1$	690
f_1+f_2	722
$2f_2-f_1$	754
$2f_1+f_2$	952
$2f_2$	984
$3f_2-2f_1$	1016

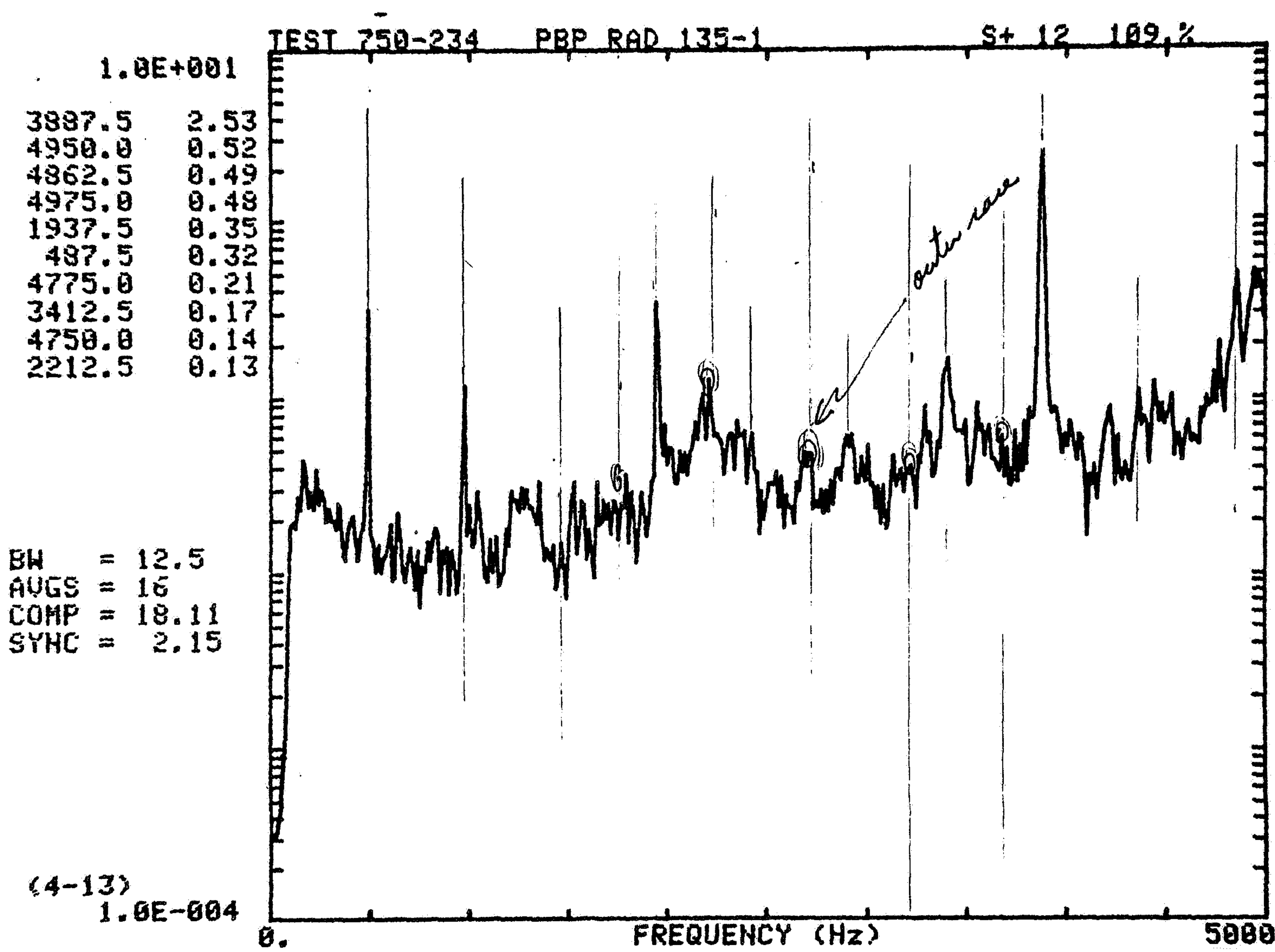


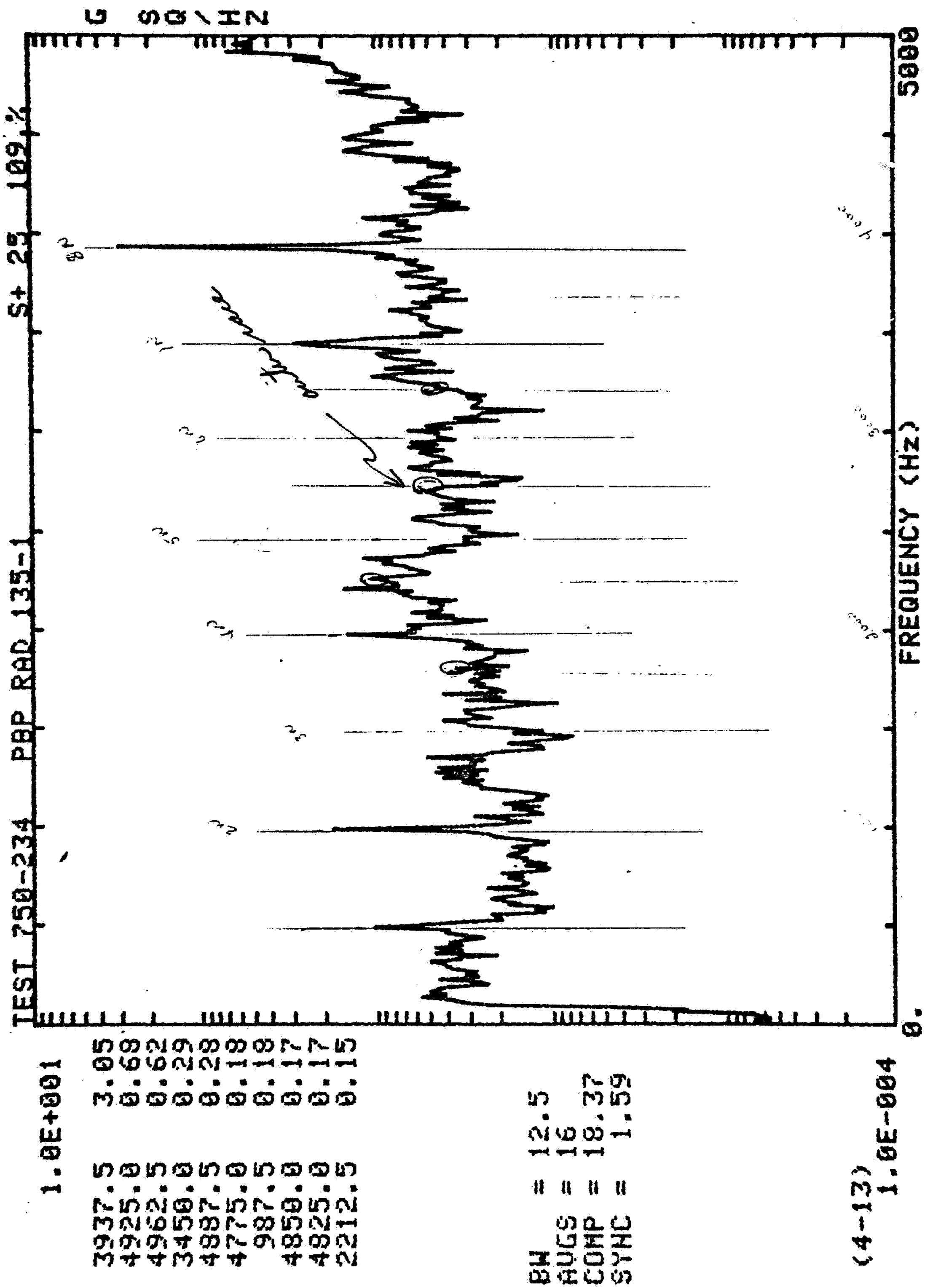
TEST 750-215 TRBN CART 60SG AC S+30 90%
1.0E+003
198 104.366
200 70.560
195 62.887
398 54.772
180 28.090
393 23.365
G S Q / H Z
BW =2.5
TIME = 6.40E+000
AVGS =16
COMP = 44.46
(5-1)
1.0E-002
0
FREQUENCY (Hz)
1000
T .47
T-N
2T
N
3T
N+T
620
4T
2N
100
200
300
400
500
600
T=198 N=420
3f1-f2 174
f1 198
f2-f1 222
2f1 396
f2 420
3f1 594
f2+f1 618
2f2-f1 642
2f1+f2 816
2f2 840
3f2-2f1 864

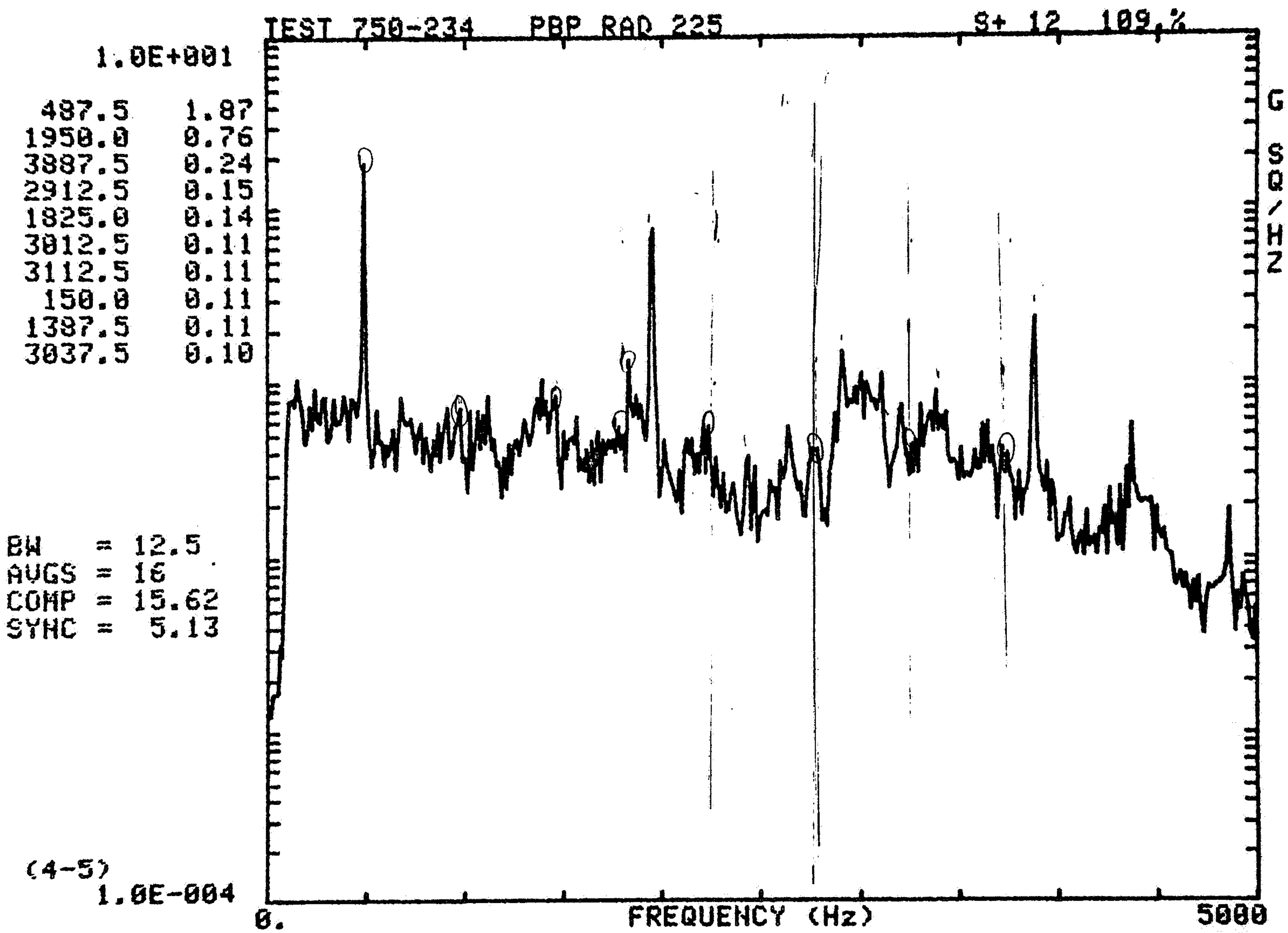

TEST 750-234 TRBN CART 60 SG AC S+ 12 109.%
1.0E+003
487.5 106.12
975.0 76.88
2750.0 9.46
2262.5 5.70
1462.5 3.77
712.5 1.22
525.0 1.14
275.0 0.88
862.5 0.69
3237.5 0.69
BW = 12.5
AVGS = 16
COMP = 61.17
SYHC = 37.21
(5-1)
1.0E-002
G SQ/HZ
0.
FREQUENCY (Hz)
5000
bearing
outer race freq.
bearing

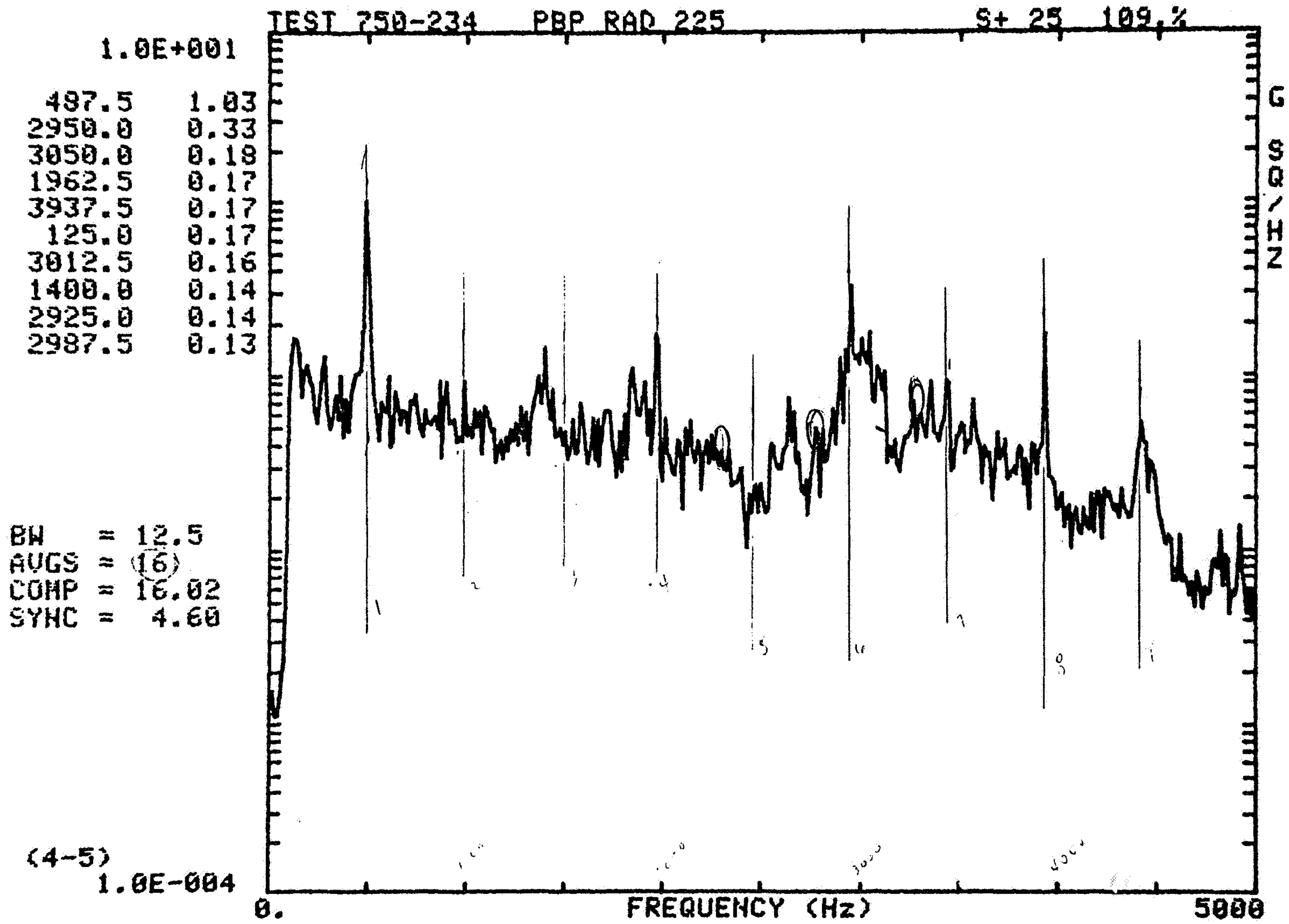

TEST 750-234 TRBN CART 60 SG AC S+ 25 109.%
1.0E+003
987.5 248.78
500.0 62.49
2775.0 8.43
1487.5 5.08
2475.0 2.73
2275.0 2.55
3962.5 2.38
3462.5 1.68
1975.0 0.99
1787.5 0.81
BW = 12.5
AVGS = 16
COMP = 78.07
SYHC = 36.10
(5-1)
1.0E-002
0.
FREQUENCY (Hz)
5000
G SQ/HZ
outer race


TEST 750-234 HPOT RAD 135 S+ 12.0 109.%
1.0E+000
3912.5 0.20
2937.5 0.19
3050.0 0.12
3025.0 0.10
3075.0 0.10
3100.0 0.09
1950.0 0.08
3125.0 0.08
3000.0 0.07
4900.0 0.07
BW = 12.5
AVGS = 32
COMP = 11.61
SYHC = 0.94
(1-6)
1.0E-005
0.
FREQUENCY (Hz)
5000
G SQ/HZ
N
2N
3N
4N
5N
6N
7N
outer race
8N
9N

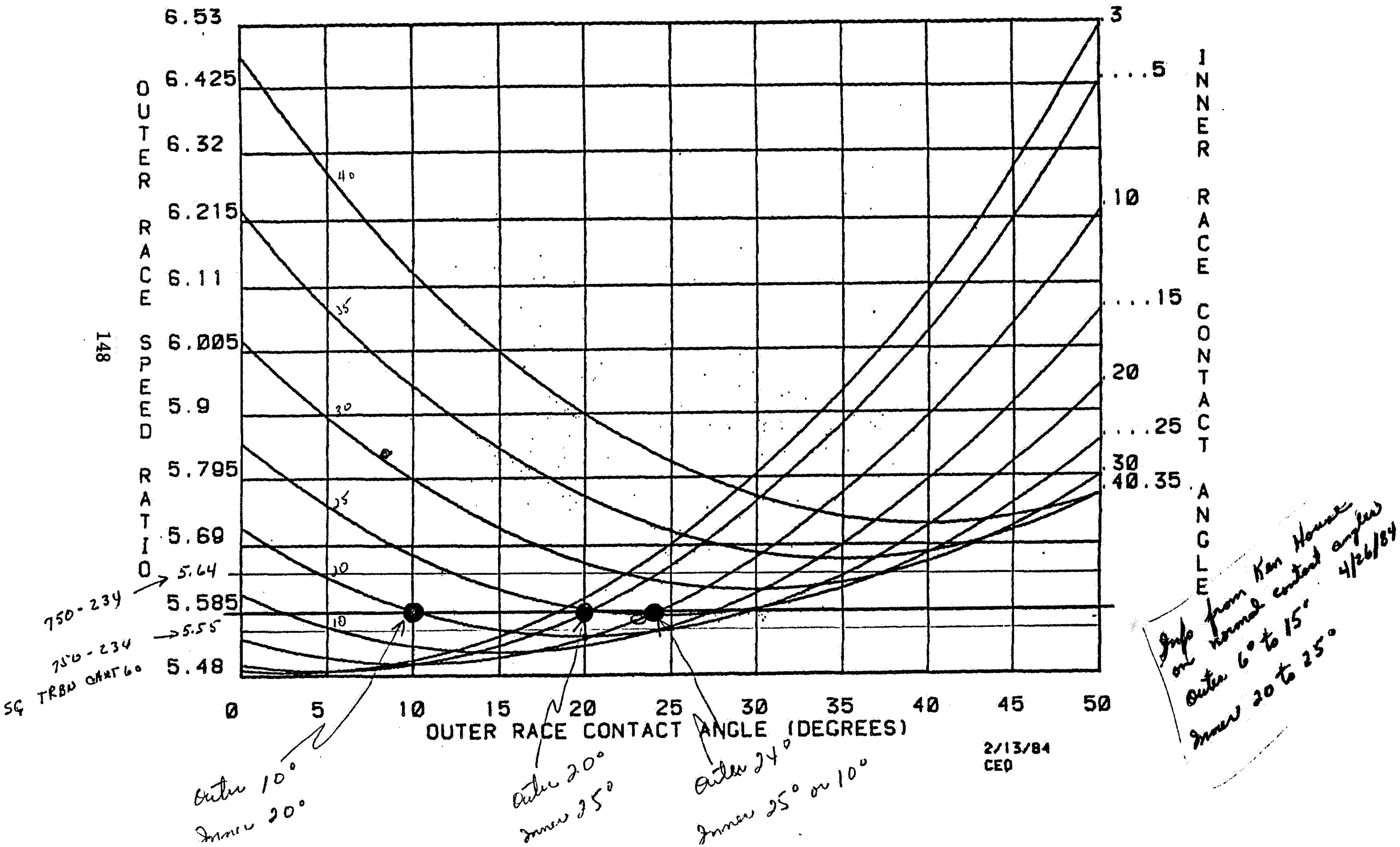

TEST 750-234 PBP RAD 135-1 S+ 12 109.%
1.0E+001
3887.5 2.53
4950.0 0.52
4862.5 0.49
4975.0 0.48
1937.5 0.35
487.5 0.32
4775.0 0.21
3412.5 0.17
4750.0 0.14
2212.5 0.13
BW = 12.5
AVGS = 16
COMP = 18.11
SYHC = 2.15
(4-13)
1.0E-004
G SQ/HZ
outer race
0.
FREQUENCY (Hz)
5000

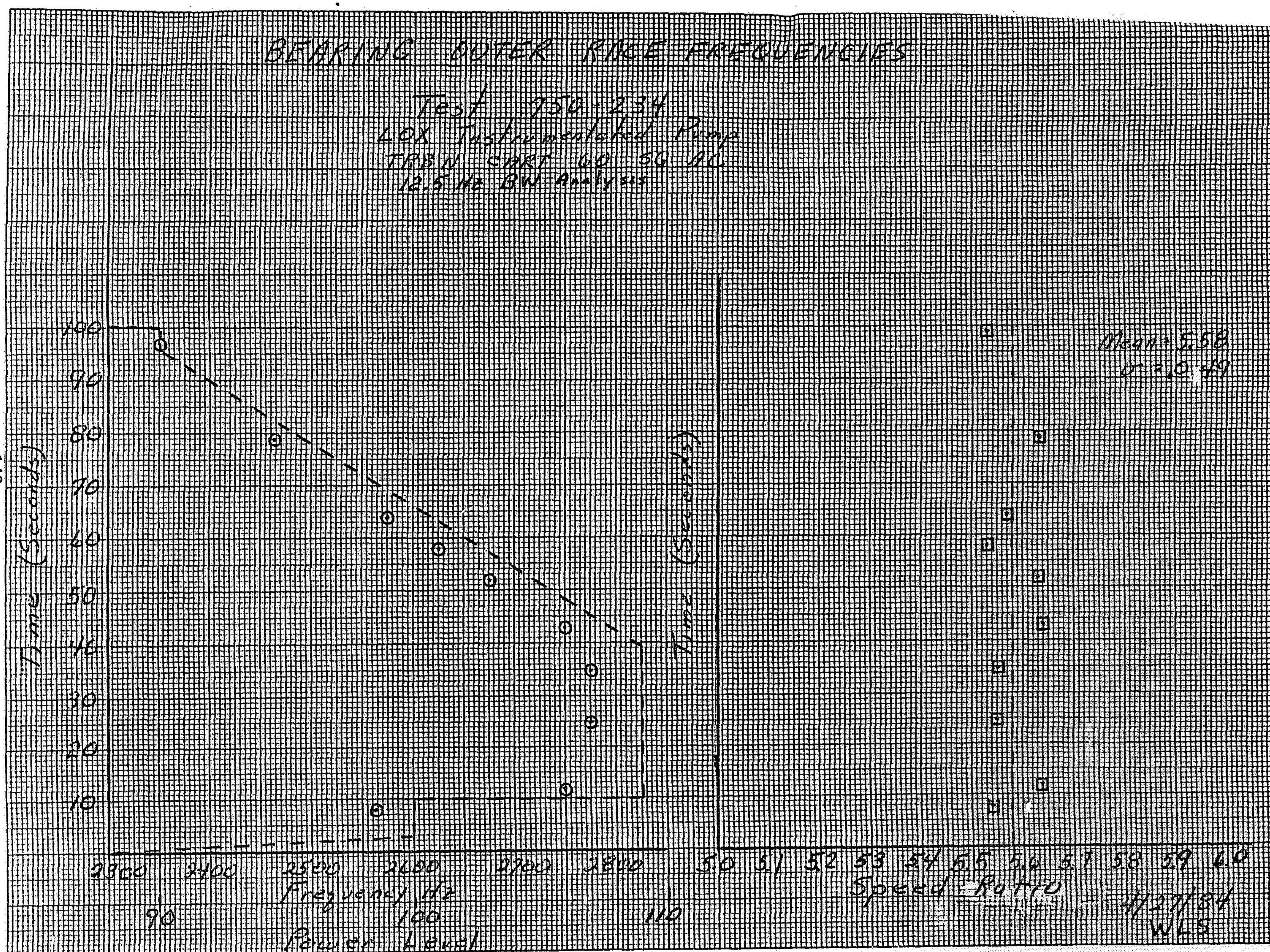

TEST 750-234 PBP RAD 135-1 S+ 25 109 %
G SQ/HZ
FREQUENCY (HZ)
0.
5000
1.0E+001
3937.5 3.05
4925.0 0.69
4962.5 0.62
3450.0 0.29
4887.5 0.28
4775.0 0.18
987.5 0.18
4850.0 0.17
4825.0 0.17
2212.5 0.15
BW = 12.5
AVGS = 16
COMP = 18.37
SYNC = 1.59
(4-13)
1.0E-004


TEST 750-234   PBP RAD 225
S+ 12   109.%
1.0E+001
487.5   1.87
1950.0   0.76
3887.5   0.24
2912.5   0.15
1825.0   0.14
3012.5   0.11
3112.5   0.11
150.0   0.11
1387.5   0.11
3037.5   0.10
BW = 12.5
AVGS = 16
COMP = 15.62
SYHC = 5.13
(4-5)
1.0E-004
0.
FREQUENCY (Hz)
5000
G SQ/HZ


TEST 750-234 PBP RAD 225
S+ 25 109.%
1.0E+001
487.5 1.03
2950.0 0.33
3050.0 0.18
1962.5 0.17
3937.5 0.17
125.0 0.17
3012.5 0.16
1400.0 0.14
2925.0 0.14
2987.5 0.13
BW = 12.5
AVGS = 16
COMP = 16.02
SYNC = 4.60
(4-5)
1.0E-004
G SQ/HZ
0.
FREQUENCY (Hz)
5000

HPOTP TURBINE BEARINGS PARAMETRIC STUDY
BALL DIAMETER=0.50000 PITCH DIAMETER=3.1960 NUMBER BALLS= 13




BEARING OUTER RACE FREQUENCIES
Test 750-234
LOX Instrumented Pump
TRBN CART 60 5G AC
12.5 Hz BW Analysis
Mean = 5.58
σ = 0.49
Time (Seconds)
100
90
80
70
60
50
40
30
20
10
2300
2400
2500
2600
2700
2800
Frequency, Hz
90
100
110
Power Level
5.0
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
6.0
Speed Ratio
4/27/84
WLS

APPENDIX C

WYLE LABORATORIES - RESEARCH STAFF
TECHNICAL MEMORANDUM 64058-01-TM

STATISTICAL ANALYSIS OF THE VIBRATION DATA FOR THE SSME HIGH PRESSURE TURBOPUMPS DURING FLIGHT

APPENDIX C

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STATISTICAL ANALYSIS OF THE VIBRATION DATA FOR THE SSME HIGH PRESSURE TURBOPUMPS DURING FLIGHT

by

Wayne L. Swanson

An interim report of
work performed under contract NAS8-33508

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

FOREWORD

Wyle Laboratories' Scientific Services & Systems Group prepared this report for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. The work was performed under contract NAS8-33508, entitled "Dynamic Analysis of SSME Vibration and Pressure Data." Technical assistance and encouragement were provided by Mr. W. C. Smith, MSFC/ED24. The special assistance of Mr. P. Lewallen, MSFC/ED24, is acknowledged for performing numerous modifications of the MSFC Diagnostic Data Base Program required to adapt the routine for flight data analysis and documentation. The contribution of other members of ED24 and Wyle Laboratories Research Department is also acknowledged.

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LIST OF FIGURES (Continued)

LIST OF FIGURES (Concluded)

1.0 INTRODUCTORY SUMMARY

This report documents the results of a statistical evaluation of RMS (root-mean-square) vibration levels measured during flight of the Space Shuttle. The data was recorded on-board the Orbiter, from accelerometers located on the Space Shuttle Main Engine (SSME) high pressure oxidizer turbopumps (HPOTP) and high pressure fuel turbopumps (HPFTP). It should be noted that the data recorded on-board the Shuttle vehicle has a 50-800 Hz bandpass filter and was analyzed using a 50-1000 Hz bandwidth. Ground test data are acquired over a wider frequency range. Therefore, any direct comparison of the composite vibration levels of the flight data to measurements recorded at the ground test stands without the bandpass filter will require the application of a small correction factor. However, the synchronous vibration levels will compare directly.

The evaluation included the composite and synchronous vibration levels at 65%, 100% and 104% power levels. Results are presented in the form of summary sheets listing the mean and standard deviation for each individual measurement; plots of the cumulative distribution with a Gamma distribution overlay, and a plot of the density function. Also presented is the ratio of the synchronous to composite vibration levels for the high pressure fuel and oxidizer turbopumps during 100% and 104% power levels.

Plots are presented of the Normal, Rayleigh, and Gamma Probability Distribution functions for comparison with over a thousand measured ground test data points. The data represents the oxidizer composite and synchronous vibration levels from ground static firings conducted on the A1, A2, and A3 test stands. An examination of the plots demonstrates the Gamma distribution function should provide reasonable approximations to the flight data. The application of a classical distribution is desirable for data characterization since this permits continuous statistical definition and manipulation from discrete flight measurement observations. Sketches are included of the accelerometer measurement locations and the power profile plots for each flight.

All of the plots contained in this report are the automatic output of the menu driven MSFC Diagnostic Data Base Program. Details of the program are documented in Reference 1.

2.0 TECHNICAL DISCUSSION

2.1 Space Shuttle Flights

Table I summarizes the 19 flights of the Space Shuttle as of August 1985.[1] The data analysis is based upon 18 flights, since only the mean square vibration levels sampled at 100 msec intervals were recorded on STS-9. This type of data is not compatible with the analysis methods used for this report. Included in Table I are the launch date, Space Shuttle Vehicle identification, maximum power level during flight, engine serial number, HPOTP serial number, and HPFTP serial numbers.

2.2 Measurement Location

The measurement locations on the HPOTP are shown in Figure 1 with the block arrangements for the 135°-1 and 135°-2 locations shown in Figure 2. A few of the early flights had measurements located at the 180° position, while the present flight measurement program is standardized to 3 measurements at the 45°, 135°-1 and 135°-2 positions. No measurements during flight are located on the High Pressure Oxidizer Turbine (HPOT) or the low pressure oxidizer turbopumps (LPOTP).

Figure 3 shows the measurement locations for the HPFTP. The measurement location of early flights was also somewhat different for the fuel turbopump than the present standardized plan of 3 measurements at the 0°, 174° and 186° positions. Data recorded at 180° position on the early flights is listed at the 186° location for the purpose of storage in the computer data bank. In addition, a few flights included data at the 90° position rather than the present 0° location. No measurements are located on the high pressure fuel turbine (HPFT) end or the low pressure fuel turbopump (LPFTP) during flight. All measurements are in the radial direction for both the HPOTP and HPFTP. The relationship of the accelerometer measurement location plane to the SSME powerhead components is shown in Figure 4.

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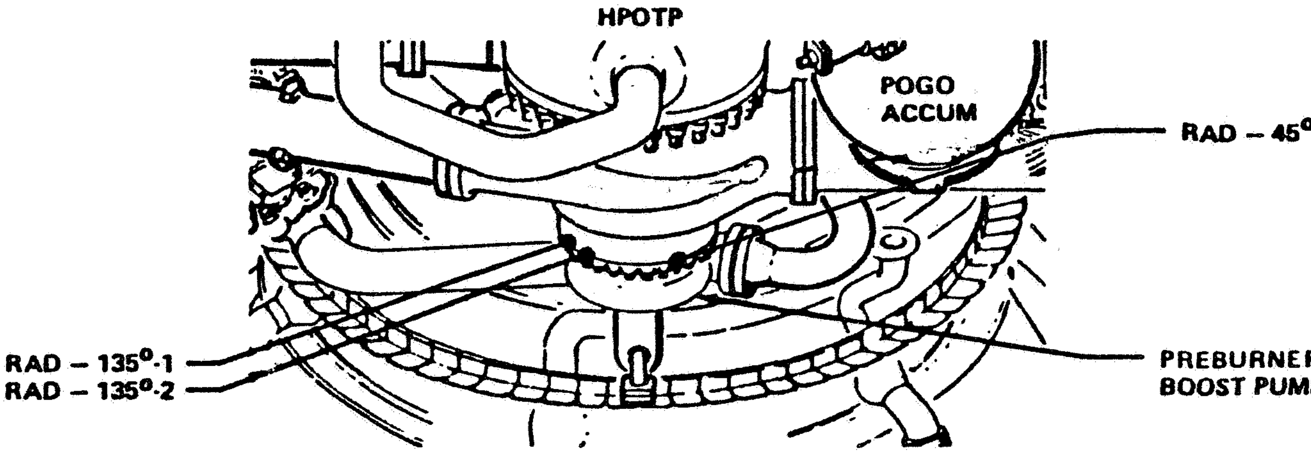
[1] Appendix A includes results from flights 27 (51-I) and 28 (51-J) which were not available at the time the statistical analysis was performed. The vibration levels of both flights were nominal and will not provide a significant change to the statistical values of this report. As additional flight data becomes available, this report will be periodically updated.

TABLE I. SHUTTLE FLIGHT

STS LAUNCH	LAUNCH DATE	OV/FLT*	POWER LEVEL	SSME 1 + 2 + 3	HPOP 1 + 2 + 3	HPFP 1 + 2 + 3
1	04/12/81	102-1	100	2007 + 2006 + 2005	0007R1 + 2404 + 2105	9006R1 + 0306R2 + 0009R1
2	11/12/81	102-2	100	2007 + 2006 + 2005	0007R1 + 2404 + 2105	9006R1 + 0306R2 + 0009R1
3	03/22/82	102-3	100	2007 + 2006 + 2005	0007R1 + 2404 + 2105R1	9006R1 + 0306R2 + 0009R1
4	06/27/82	102-4	100	2007 + 2006 + 2005	0007R1 + 2404 + 2105R1	2009 + 0306R2 + 0009R2
5	11/11/82	102-5	100	2007 + 2006 + 2005	9009R3 + 2404 + 2105R1	2009 + 0306R2 + 9006R2
6	04/04/83	099-1	104	2017 + 2015 + 2012	9010 + 2015 + 2016	9110 + 2315 + 2213R1
7	06/18/83	099-2	104	2017 + 2015 + 2012	9010 + 2015 + 2016	2315 + 9211 + 2213R1
8	08/30/83	099-3	100	2017 + 2015 + 2012	9010 + 2015 + 2016	2315 + 9211 + 2116R2
9(41-A)	11/28/83	102-6	104	2011 + 2018 + 2019	2018 + 9211 + 2019	2017R1 + 2213R1 + 9210
11(41-B)	02/03/84	099-4	100	2109 + 2015 + 2012	2020 + 2015 + 2016	5101R1 + 9211 + 2116R2
13(41-C)	04/06/84	099-5	104	2109 + 2020 + 2012	2020 + 2021 + 2016	5101R1 + 2018 + 2116R2
14(41-D)	08/30/84	103-1	104	2109 + 2018 + 2021	2020 + 9211 + 4001	2020R2 + 2017R2 + 4001R1
17(41-G)	10/05/84	099-6	100	2023 + 2020 + 2021	2019R1 + 2021 + 4001	2515R1 + 9311R1 + 4001R1
19(51-A)	11/08/84	103-2	104	2109 + 2018 + 2012	2020 + 9211 + 9110	2020R2 + 2017R2 + 2118
20(51-C)	01/24/85	103-3	104	2109 + 2018 + 2012	2020 + 2018R1 + 9110	4202 + 2017R2 + 4003
23(51-D)	04/12/85	103-4	100	2109 + 2018 + 2012	2115 + 2018R1 + 9110	4202 + 2017R2 + 4003
24(51-B)	04/29/85	099-7	104	2023 + 2020 + 2021	2019R1 + 2021 + 4001	2515R1 + 9311R1 + 2216
25(51-G)	06/17/85	103-5	104	2109 + 2018 + 2012	2115 + 2016R3 + 9110	2121 + 4201R2 + 4003R1
26(51-F)	07/29/85	099-8	104	2023 + 2020 + 2021	2019R1 + 4003R1 + 4001	2515R1 + 4202R1 + 2216
**27(51-I)	08/27/85	103-5	104	2109 + 2018 + 2021	2115 + 2016R3 + 2018R2	2121R1 + 4201R2 + 4003R1
**28(51-J)	10/05/85	104-1	104	2011 + 2019 + 2017	2022R2 + 9211R2 + 4102R1	5301 + 2120 + 2218R1

* OV-099 Challenger; OV-102 Columbia; OV-103 Discovery; OV-104 Atlantis

** The data of STS Launch 27 (51-I) and 28 (51-J) are included in Appendix A. Both flights were nominal and will not influence the statistical data contained in this report.



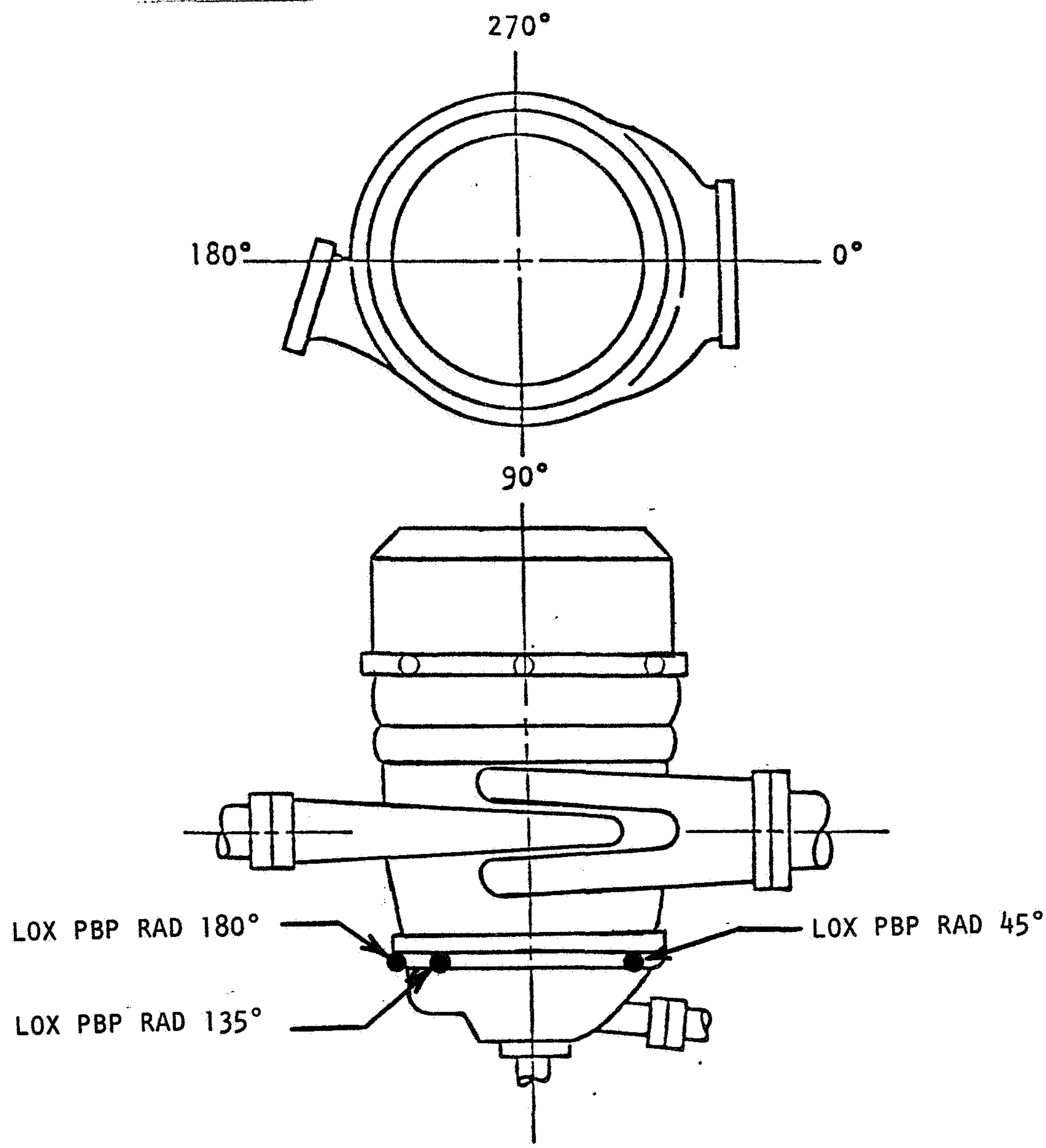


Figure 1. High Pressure Oxidizer Turbopump Accelerometer Locations, Flight

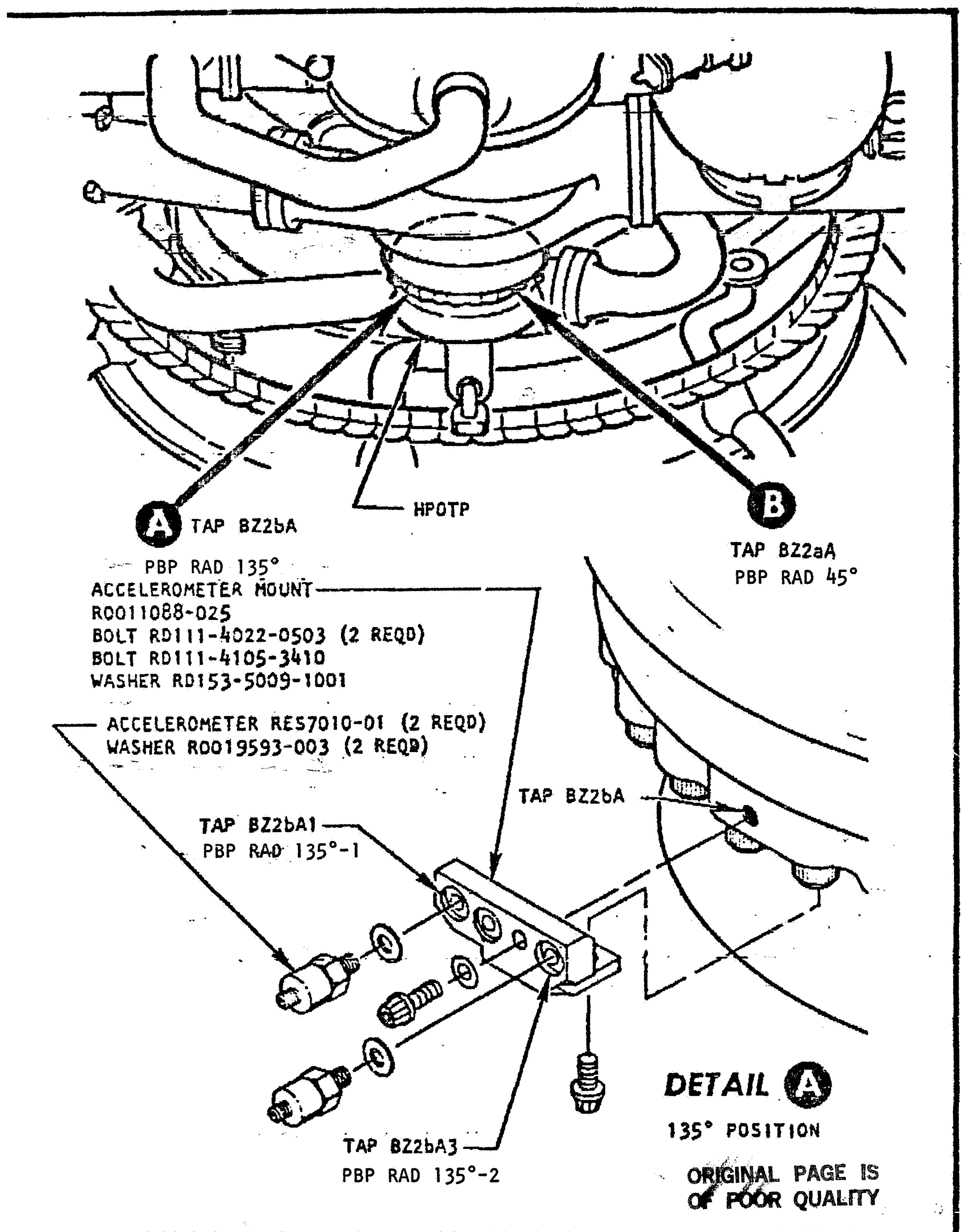


Figure 2. HPOTP Accelerometer Block 135°-1 and 135°-2, Flight

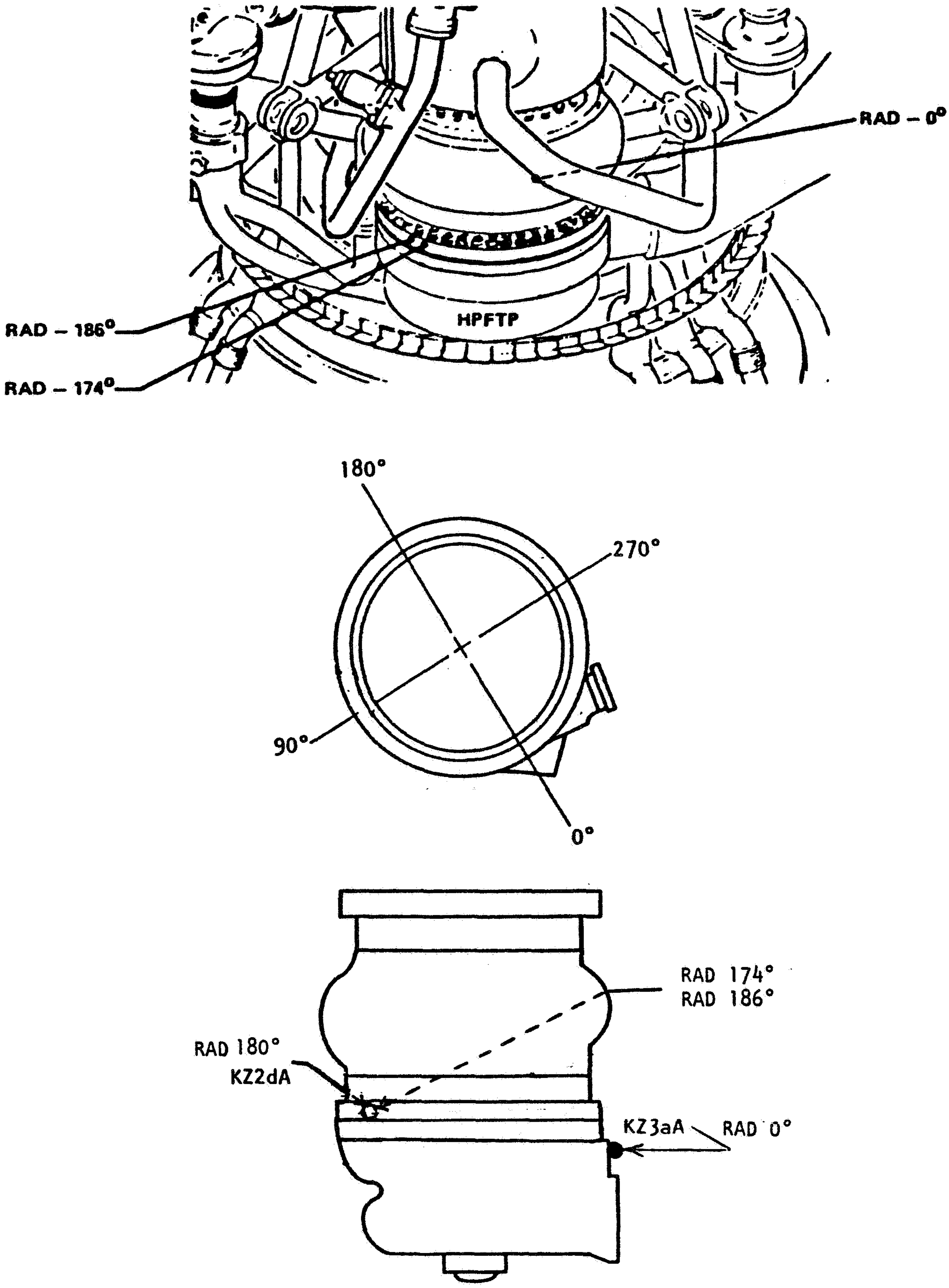


Figure 3. High Pressure Fuel Turbopump Accelerometer Locations, Flight

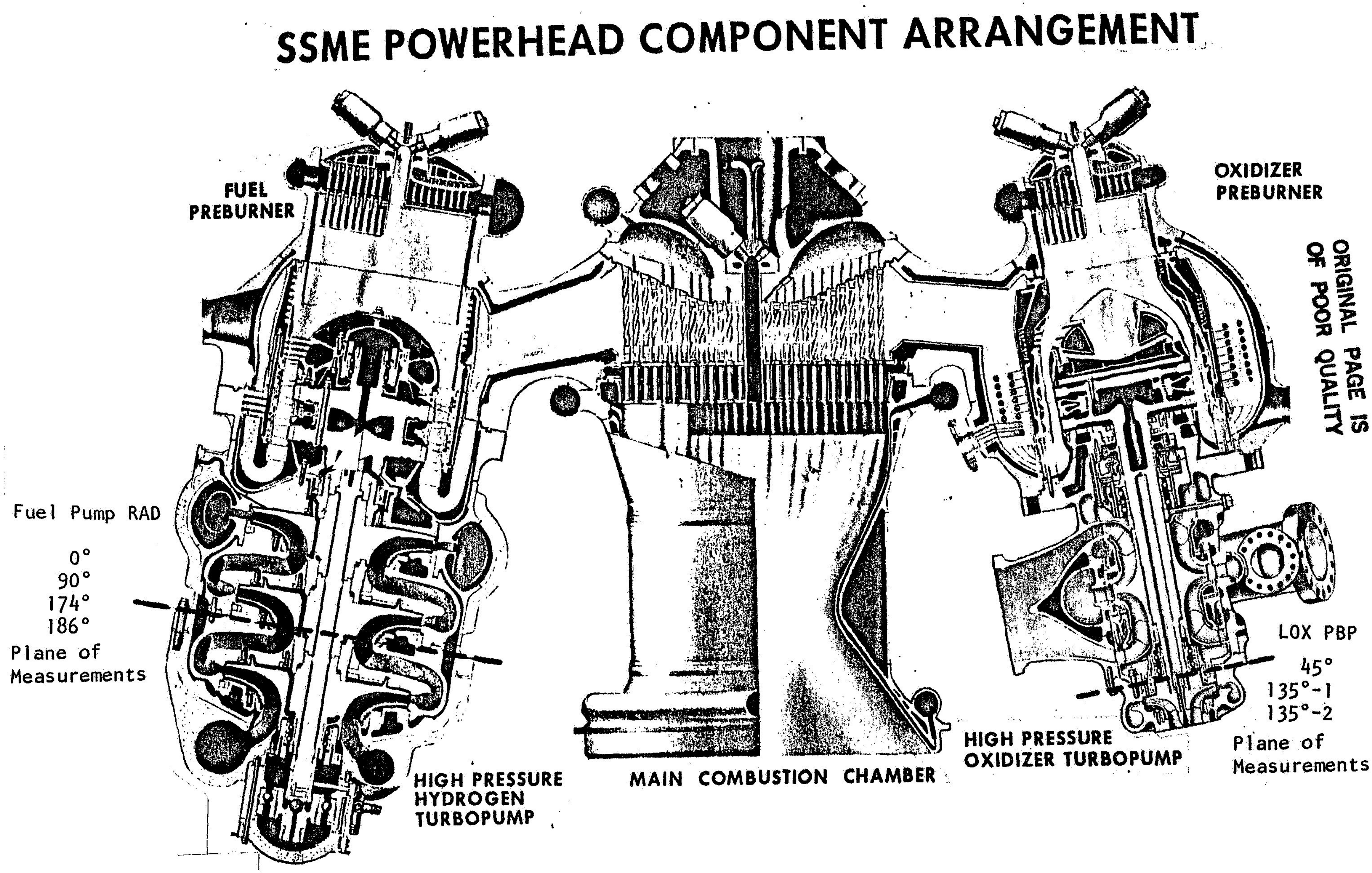


Figure 4. Accelerometer Location Plane, Flight

2.3 Power Profiles

The power profiles for each of the 18 flights are shown in Figures 5 through 8. The profiles for all ground tests and flights are stored in the MSFC Diagnostic Data Bank for retrieval and plotting. It should be noted that two profiles are shown for Mission STS 51-F indicating the early cutoff of engine number 1 during this flight.

2.4 Mean and Standard Deviation of Vibration Measurements

Given a data sample of size N the mean and variance are defined by

$$\bar{x} = 1/N \sum_{N} x_i \qquad \text{(Sample Mean)} \qquad (2.4\text{-}1)$$

$$\bar{\sigma}^2 = 1/(N-1) \sum_{N} (x_i - \bar{x})^2 \qquad \text{(Sample Variance)} \qquad (2.4\text{-}2)$$

The standard deviation is the positive square root of the variance and defined by

$$SD = \sqrt{\frac{1}{N\text{-}1} \sum_{N} (x_i - \bar{x})^2} \qquad \text{(Sample Standard Deviation)} \qquad (2.4\text{-}3)$$

2.4.1 Combined Data Groups

Each of the above statistics was first calculated for each measurement location and then combined as necessary for printout or plotting. The following is a discussion of procedures for combining data depending on whether the sums and the sum of squared terms or only the mean and standard deviation are stored.

Assume we wish to combine the vibration levels measured on the LOX PBP 135°-1 with the levels measured on LOX PBP 135°-2, where the mean and standard deviation were calculated for each measurement. If the sums and sum of squared terms are stored the combined mean and standard deviation are as follows.

$$\bar{x}_{12} = \frac{\sum_{N_1} (x_i)_1 + \sum_{N_2} (x_i)_2}{N_1 + N_2} \qquad (2.4\text{-}4)$$

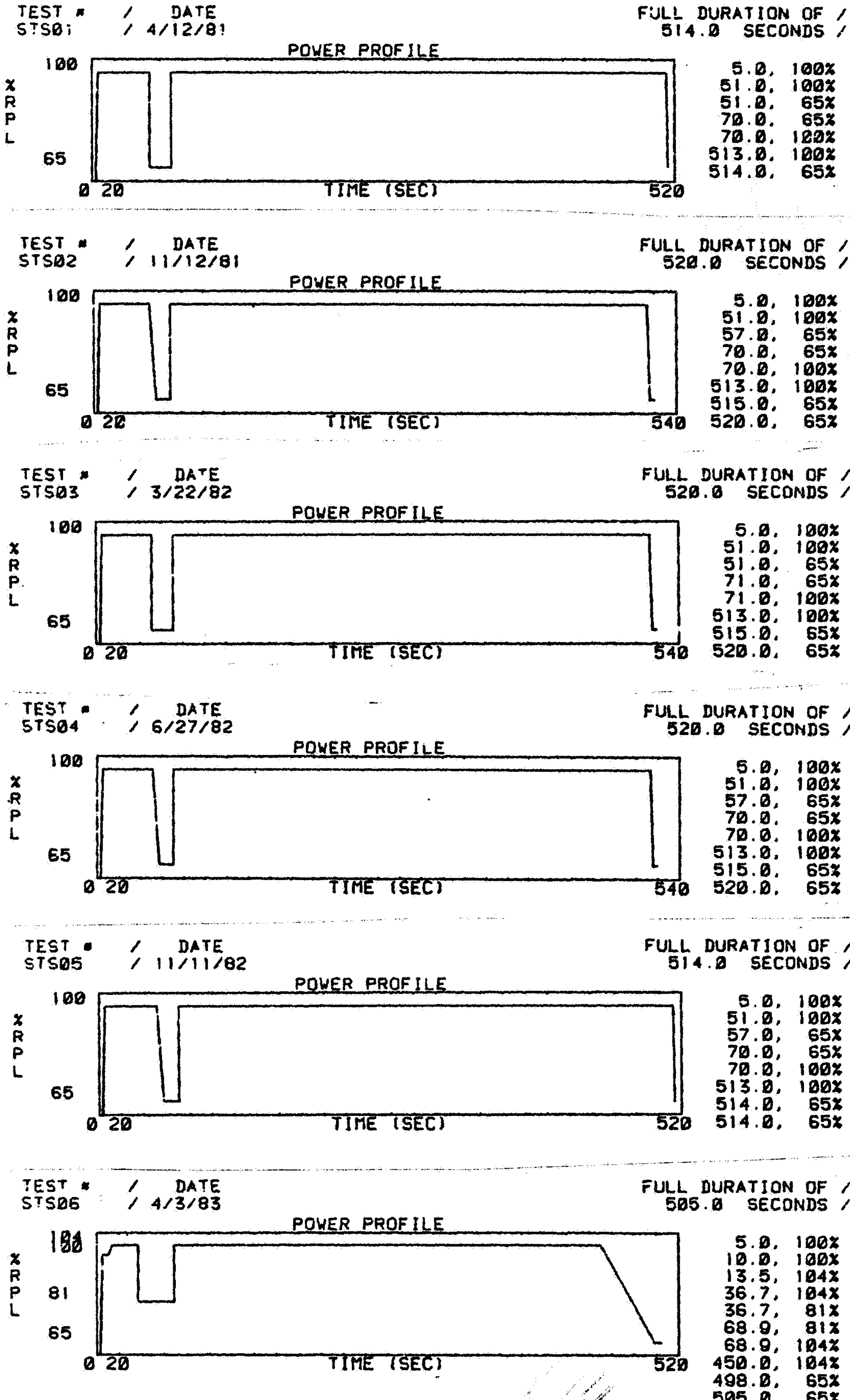
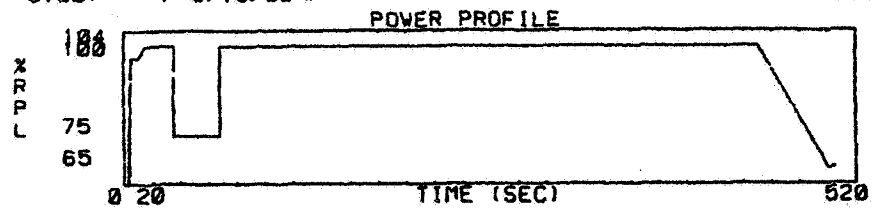


Figure 5. Flight Power Profile, STS-1 to STS-6

TEST # / DATE
STS07 / 6/18/83

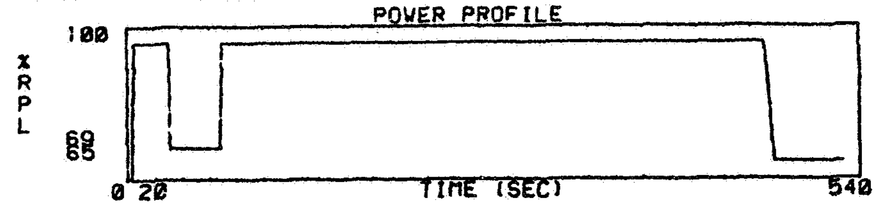
FULL DURATION OF / 505.0 SECONDS /



5.0,	100%
10.0,	100%
15.0,	104%
35.0,	104%
35.0,	75%
68.0,	75%
68.0,	104%
450.0,	104%
500.0,	65%
505.0,	65%

TEST # / DATE
STS08 / 2/20/81

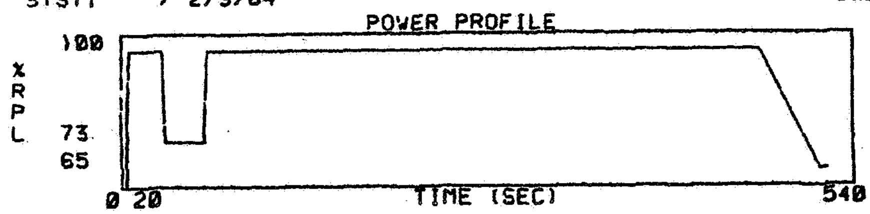
FULL DURATION OF / 528.0 SECONDS /



5.0,	100%
30.0,	100%
31.0,	69%
67.5,	69%
69.0,	100%
470.0,	100%
477.0,	65%
528.0,	65%

TEST # / DATE
STS11 / 2/3/84

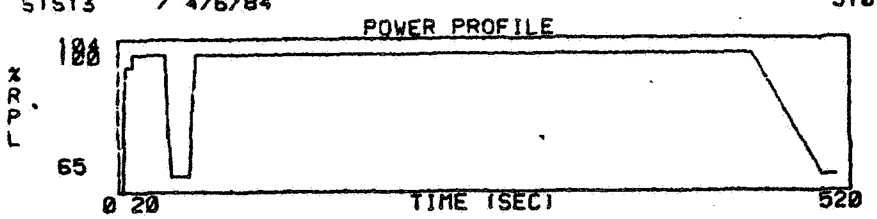
FULL DURATION OF / 520.9 SECONDS /



5.0,	100%
29.7,	100%
32.2,	73%
60.7,	73%
63.1,	100%
470.2,	100%
514.8,	65%
520.9,	65%

TEST # / DATE
STS13 / 4/6/84

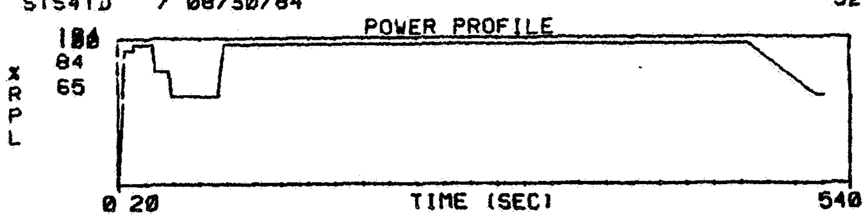
FULL DURATION OF / 510.0 SECONDS /



5.0,	100%
9.6,	100%
10.1,	104%
33.0,	104%
37.0,	65%
50.0,	65%
55.0,	104%
450.0,	104%
500.0,	65%
510.0,	65%

TEST # / DATE
STS41D / 08/30/84

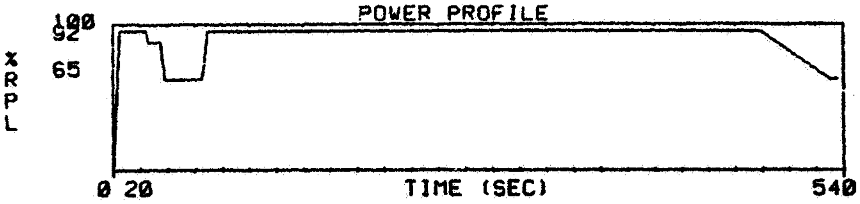
FULL DURATION OF / 521.0 SECONDS /



0.0,	0%
5.0,	100%
10.7,	100%
11.1,	104%
25.0,	104%
27.0,	84%
37.0,	84%
38.9,	65%
73.0,	65%
77.9,	104%
465.0,	104%
515.0,	65%
521.0,	65%

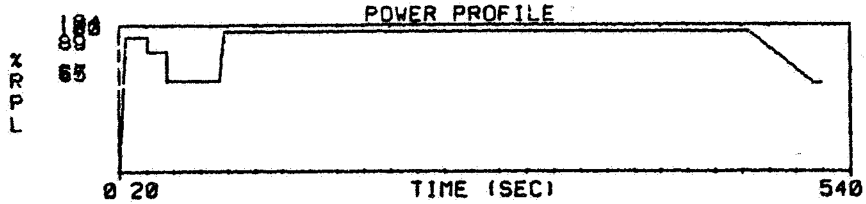
Figure 6. Flight Power Profile, STS-07 to STS-41D

TEST # / DATE FULL DURATION OF /
STS41G / 10/5/84 536.0 SECONDS /



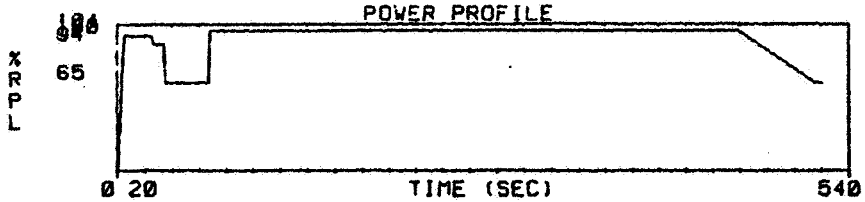
0.0,	0%
5.0,	100%
15.0,	100%
24.7,	100%
26.0,	92%
35.0,	92%
38.0,	65%
54.0,	65%
65.0,	65%
69.0,	100%
80.0,	100%
100.0,	100%
115.0,	100%
135.0,	100%
240.0,	100%
255.0,	100%
355.0,	100%
478.0,	100%
530.0,	65%
536.0,	65%

TEST # / DATE FULL DURATION OF /
STS51A / 11/8/84 520.0 SECONDS /



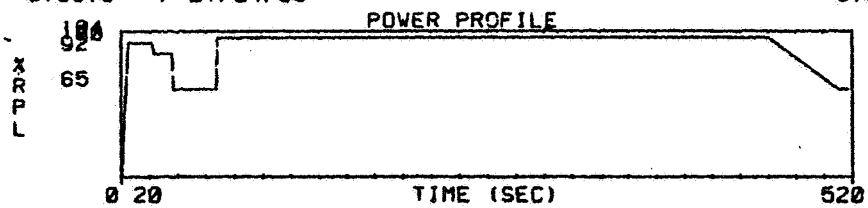
0.0,	0%
5.0,	100%
21.1,	100%
21.2,	89%
35.0,	89%
35.1,	67%
74.0,	67%
77.5,	104%
464.8,	104%
513.1,	65%
520.0,	65%

TEST # / DATE FULL DURATION OF /
STS51B / 4/30/85 521.0 SECONDS /



0.0,	0%
5.0,	100%
25.0,	100%
26.0,	94%
34.0,	94%
35.0,	65%
67.0,	65%
68.0,	104%
459.0,	104%
515.0,	65%
521.0,	65%

TEST # / DATE FULL DURATION OF /
STS51C / 01/24/85 518.0 SECONDS /



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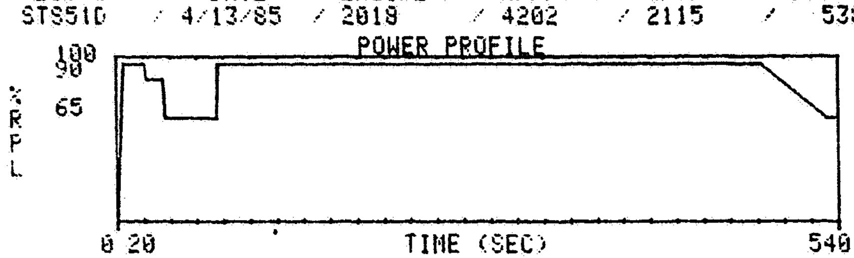
STS51D / 4/13/85 / 2018 / 4202 / 2115 / 538.0 SECONDS /



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532.0,	65%
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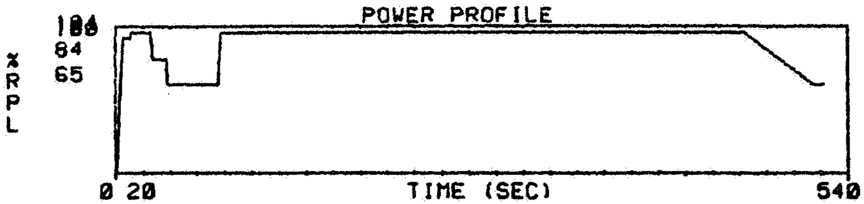
Figure 7. Flight Power Profile STS-41G to STS-51D

TEST # / DATE FULL DURATION OF /
STS51G / 06/17/85 523.0 SECONDS /



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27.0,	84%
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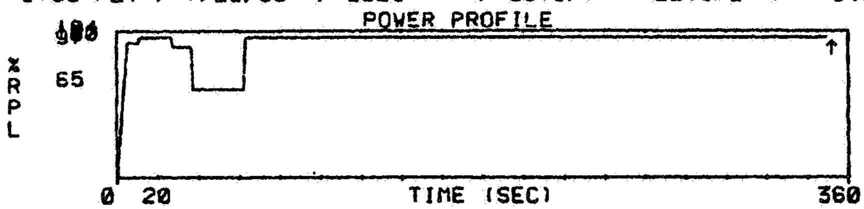
75.0,	65%
77.0,	104%
462.6,	104%
514.0,	65%
523.0,	65%

TEST # / DATE / ENGINE # / HPFPT # / HPOPT # / EARLY CUTOFF AT /
STS51FE1 / 7/29/85 / 2023 / 2515R1 / 2010R2 / 349.7 SECONDS /



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27.0,	97%
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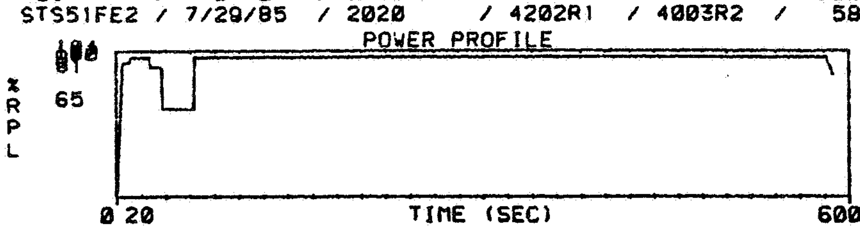
62.0,	65%
63.0,	104%
349.7,	104%

TEST # / DATE / ENGINE # / HPFPT # / HPOPT # / FULL DURATION OF /
STS51FE2 / 7/29/85 / 2020 / 4202R1 / 4003R2 / 588.0 SECONDS /



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10.1,	100%
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26.0,	104%
27.0,	97%
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37.0,	65%
62.0,	65%
63.0,	104%
582.0,	104%
587.0,	91%
588.0,	91%

Figure 8. Flight Power Profile, STS-41G to STS-51F

where N_1 and $(x_i)_1$ are the number of measurements and vibration value respectively of the LOX PBP 135°-1 location, N_2, $(x_i)_2$ the values of the LOX PBP 135°-2 location and $\bar{x}_{12}$ is the combined mean vibration value.

Equation (2.4-3) for calculation of the standard deviation is modified to a format where the only requirement is storage of the sums. Using Equations (2.4-1) and (2.4-3)

$$SD = \sqrt{\frac{1}{N-1} \sum_N (x_i - \bar{x})^2} \tag{2.4-5}$$

$$(SD)^2 (N-1) = \sum_N (x_i - \bar{x})^2$$

$$= \sum_N (x_i^2 - 2x_i \bar{x} + \bar{x}^2)$$

$$= \sum_N (x_i)^2 - \sum 2 x_i \bar{x} + \sum (\bar{x})^2$$

Since

$$\sum_N 2 x_i = 2 N \bar{x}$$

and

$$\sum_N (\bar{x})^2 = N(\bar{x})^2$$

$$(SD)^2 (N-1) = \sum_N (x_i)^2 - 2N(\bar{x})^2 + N(\bar{x})^2$$

$$= \sum_N (x_i)^2 - N(\bar{x})^2$$

and

$$SD = \sqrt{\frac{\sum_{N} (x_i)^2 - N(\bar{x})^2}{N-1}} \qquad (2.4\text{-}6)$$

or

$$SD = \sqrt{\frac{\sum_{N} (x_i)^2 - \frac{(\sum_{N} x_i)^2}{N}}{N-1}} \qquad (2.4\text{-}7)$$

As can be easily seen from examination of Equation (2.4-7), only the number of data points and the sum of x_i and $(x_i)^2$ values are required for calculation of the standard deviation. Most hand calculators and computer programs use this method rather than Equations (2.4-1) and (2.4-3). Equations (2.4-1) and (2.4-3) require the calculation of the mean for the complete data set before the sum of the difference squared can be calculated.

The standard deviation for the combined LOX PBP 135°-1 and LOX PBP 135°-2, assuming the sum of the x_i and $(x_i)^2$ terms are available is

$$SD_{12} = \sqrt{\frac{\sum_{N_1} (x_i)_1^2 + \sum_{N_2} (x_i)_2^2 - \left[\frac{\left[\left(\sum_{N_1} x_i\right)_1 + \left(\sum_{N_2} x_i\right)_2\right]^2}{N_1 + N_2}\right]}{N_1 + N_2 - 1}} \qquad (2.4\text{-}8)$$

However, if the sums are not available the combined mean and standard deviation can be calculated from the individual number of data points, means and standard deviations as follows.

From Equation (2.4-1)

$$\sum_{N} x_i = N\bar{x} \qquad (2.4\text{-}9)$$

and with Equation (2.4-4) the combined mean of the LOX PBP 135°-1 and LOX PBP 135°-2 is

$$\bar{x}_{12} = \frac{N_1 \bar{x}_1 + N_2 \bar{x}_2}{N_1 + N_2} \qquad (2.4\text{-}10)$$

where the subscripts 1 and 2 of N and $\bar{x}$ indicate the number of data points and mean of the individual data sets, respectively.

For the calculation of the standard deviation using Equations (2.4-1), (-6), and (-8)

$$\sum_N x_i = N \bar{x}$$

$$\sum_N (x_i)^2 = (SD)^2 (N-1) + N(\bar{x})^2$$

and substitution into Equation (2.4-8)

$$(SD_{12})^2 (N_1 + N_2 - 1) = (SD)_1^2 (N_1 - 1) + N_1 (\bar{x})_1^2 + (SD)_2^2 (N_2-1) + N_2(\bar{x})_2^2 - \left[\frac{(N_1 \bar{x}_1 + N_2 \bar{x}_2)^2}{N_1 + N_2}\right]$$

and the combined standard deviation of the LOX PBP 135°-1 and LOX PBP 135°-2 is

$$SD_{12} = \sqrt{\frac{(SD)_1^2 (N_1-1) + (SD)_2^2 (N_2-1) + N_1 (\bar{x}_1)^2 + N_2 (\bar{x}_2)^2 - \left[\frac{(N_1\bar{x}_1+N_2\bar{x}_2)^2}{N_1 + N_2}\right]}{N_1 + N_2 - 1}} \qquad (2.4\text{-}11)$$

The procedure can be repeated if an additional data set, for example the LOX PBP RAD 45°, is to be combined with the LOX PBP RAD 135°-1 and LOX PBP RAD 135°-2 data set. A more elegant derivation of the equations for combining multiple data sets, augmenting a data set and deleting a data point from unpublished work of Tom Coffin is included in the next section. A procedure for combining data based on the small sample size theorem for the high order moments (skewness and kurtosis) will be forthcoming in future documentation.

2.5 Formulae for Estimating Basic Engine Parameter Statistics

2.5.1 Background

Given a sample of size N from a population of size P, the mean and variance are defined for N and P by

$$\bar{m} = (1/N) \sum_{N} x_i \qquad \text{(Sample mean)} \qquad (2.5\text{-}1)$$

$$m = (1/P) \sum_{P} x_i \qquad \text{(Population mean)} \qquad (2.5\text{-}2)$$

$$\bar{\sigma}^2 = (1/N-1) \sum_{N} (x_i - \bar{m})^2 \qquad \text{(Sample variance)} \qquad (2.5\text{-}3)$$

$$\sigma^2 = (1/P) \sum_{P} (x_i - m)^2 \qquad \text{(Population variance)} \qquad (2.5\text{-}4)$$

Note that for large N,

$$(N/N-1) \rightarrow 1,$$

so formula 3 approaches

$$\bar{\sigma}^2 \simeq (1/N) \sum_{N} (x_i - \bar{m})^2 \qquad \text{(for large N)} \qquad (2.5\text{-}3A)$$

The asymptotic convergence between formulae 2.5-3 and -3A is more strongly emphasized by observing that the standard deviation is the primary statistic of interest, so the practical deviation between formulae 2.5-3 and -3A is as

$$\left\{ N(N-1)^{-1} \right\}^{\frac{1}{2}}$$

Since the population of possible engine parameter outcomes is infinite, our statistical estimates are based on formulae 2.5-1 and 2.5-3 or -3A.

2.5.2 Combined Multiple Data Groups

Next, assume a sample, S, consisting of three subgroups, $\{X\}$, $\{Y\}$, $\{Z\}$. Technically

$$S = X \cup Y \cup Z \tag{2.5-5}$$

A practical example would be to let X, Y, Z represent a parameter measured on test stands A_I, A_{II}, A_{III}, respectively. The set S then represents the parameter variation giving equal weight to each test from all test stands.

Assume also that we have computed $\bar{m}$ and $\bar{\sigma}$ for each of these groups and wish to compute the same statistics for the complete set (2.5-5). It is desirable to use the group statistics already calculated to obtain these results, as opposed to applying formulae 2.5-1 and 2.5-3 on the complete data set. More specifically, given

$$\bar{m}_X, \bar{m}_Y, \bar{m}_Z; \bar{\sigma}_X, \bar{\sigma}_Y, \bar{\sigma}_Z$$

compute $\bar{m}_S, \bar{\sigma}_S$, where S is defined by formula 2.5-5.

First, consider the mean $\bar{m}_S$. By formula 2.5-1,

$$\bar{m}_s = (1/N_S)\left[\sum_{N_X} x_i + \sum_{N_Y} y_i + \sum_{N_Z} z_i\right] \tag{2.5-6}$$

where $$N_S = N_X + N_Y + N_z. \tag{2.5-7}$$

But also by formula 2.5-1,

$$\begin{aligned} \sum_{N_X} x_i &= N_X\bar{m}_X \\ \sum_{N_Y} y_i &= N_Y\bar{m}_Y \\ \sum_{N_Z} z_i &= N_Z\bar{m}_Z \end{aligned} \tag{2.5-8}$$

so $$\bar{m}_S = (1/N_S)\left[N_X\bar{m}_X + N_y\bar{m}_Y + N_Z\bar{m}_Z\right] \tag{2.5-9}$$

Or, more compactly,

$$\bar{m}_S = (1/N_S) \sum_j N_j \bar{m}_j \qquad (2.5\text{-}10)$$

where $\quad N_S = \sum_j N_j.$

Next consider the variance, $\bar{\sigma}_S^2$. By formula 2.5-3,

$$\bar{\sigma}_S^2 = (1/N_S-1) \left\{ \sum_{N_X} (x_i-\bar{m}_S)^2 + \sum_{N_Y} (y_i-\bar{m}_S)^2 + \sum_{N_Z} (z_i-\bar{m}_S)^2 \right\} \qquad (2.5\text{-}11)$$

Expanding the first sum in brackets,

$$\sum_{N_X} (x_i-\bar{m}_S)^2 = \sum_{N_X} x_i^2 - 2N_X\bar{m}_X\bar{m}_S + N_X\bar{m}_S^2, \qquad (2.5\text{-}12)$$

and noting that by formula 2.5-3,

$$\sum_{N_X} x_i^2 = (N_X-1)\,\bar{\sigma}_X^2 + N_X\bar{m}_X^2 \qquad (2.5\text{-}13)$$

the first sum in formula 2.5-11 may be written

$$\sum_{N_X} (x_i-\bar{m}_S)^2 = (N_X-1)\,\bar{\sigma}_X^2 + N_X(\bar{m}_X-\bar{m}_S)^2 \qquad (2.5\text{-}14)$$

and an identical form follows for the remaining two sums.

The variance of the combined data set may therefore be conveniently computed by the formula

$$\bar{\sigma}_S^2 = (1/N_S-1) \left\{ \sum (N_i-1)\bar{\sigma}_i^2 + \sum N_i(\bar{m}_i-\bar{m}_S)^2 \right\} \qquad (2.5\text{-}15)$$

Again, if the data groups are large (say, N_i is greater than 30),

$$\bar{\sigma}_S^2 \simeq (1/N_S)\left\{\sum N_i\,\bar{\sigma}_i^2 + \sum N_i(\bar{m}_i-\bar{m}_S)^2\right\} \tag{2.5-16}$$

2.5.3 Augmenting a Data Set

Often, means and variances may be computed for a set of data and a new data point then obtained. It is desirable to compute these statistics for the newly augmented data set using those already obtained (as opposed to starting anew).

Consider a group $\{X\}$, of size N_X, for which we have already computed $\bar{m}_X$, $\bar{\sigma}_X$ by formuale 2.5-1 and 2.5-3, respectively, and let

$$S = \left\{x_i, x_2, \ldots, x_N, Z\right\} \tag{2.5-17}$$

then, by formula 2.5-1,

$$\bar{m}_S = (1/N_X+1)\left\{\sum_{N_X} x_i + Z\right\} \tag{2.5-18}$$

or simply

$$\bar{m}_S = (1/N_X+1)\,(N_X\bar{m}_X+Z) \tag{2.5-19}$$

Finally, by formulae 2.5-3 or 2.5-11,

$$\bar{\sigma}_S^2 = (1/N_X)\left\{\sum_{N_X} (x_i-\bar{m}_S)^2 + (Z-\bar{m}_S)^2\right\} \tag{2.5-20}$$

and using 2.5-17,

$$\bar{\sigma}_S^2 = (1/N_X)\left\{(N_X-1)\,\bar{\sigma}_X^2 + N_X(\bar{m}_X-\bar{m}_S)^2 + (Z-\bar{m}_S)^2\right\} \tag{2.5-21}$$

2.5-19 and 2.5-21 provide the desired formulae.

2.5.4 Deleting a Data Point

A third situation is encountered when the mean and variance for a data set have been computed, after which it is found that an included test result is invalid. It is then convenient to have formulae available to obtain the statistics for the reduced set, for example, neglecting the invalid data point.

Let S, S' represent the complete and reduced data set, respectively. By simply rearranging 2.5-19, the mean for the reduced set is

$$\bar{m}_{S'} = \frac{N_S \bar{m}_S - Z}{N_S - 1} \tag{2.5-22}$$

where Z represents the invalid data point to be deleted. Similarly, the desired variance is obtained by manipulating formula 2.5-21:

$$\bar{\sigma}^2_{S'} = (1/N_S - 2) \left\{ (N_S - 1)\left[\bar{\sigma}^2_S - (\bar{m}_{S'} - \bar{m}_S)^2\right] - (Z - \bar{m}_S)^2 \right\} \tag{2.5-23}$$

The above formulae are easily programmed on a small calculator for ready reference, and have been implemented in the diagnostic data base software for data base editing and update.

2.6 Classical Distribution Functions

Three classical continuous probability distributions were selected for comparison with the SSME vibration data. They were the Normal, Rayleigh and Gamma functions and are listed as programmed in the Diagnostic Data Bank in the next paragraph. Since the choice of a classical probability function for a data set is arbitrary, additional investigations are planned to evaluate other classical distributions and functions of higher order. Best-Fit (Chi-Square Goodness-of-Fit, Bonferroni-Type Inequalities, etc.) will also be investigated. However, a visual inspection of Figures 9 to 32 indicates the Gamma function is reasonable for the SSME high pressure turbopump vibration data from static firing tests and should be applicable to the flight data. Plots are shown for both the composite and synchronous vibration levels. Static firing tests were utilized for the comparison, since a larger data base was available consisting of over 1,000 data samples.

The application of a classical distribution is desirable for data characterization since this permits continuous statistical definition and manipulation from discrete flight measurement observations. The cumulative distribution plots provide a quick-look assessment of flight results with the historical distribution of measurements from previous flights. Density plots are useful for an assessment of the historical data scatter or dispersion around the mid-point or mean value. The density functions are shown in Figures 15 to 20 for the composite values and Figures 27 to 32 for the synchronous values from which the cumulative distribution was calculated from

$$F(N\Delta x) = \sum_{i=1}^{N} f(x_i) \qquad (2.6\text{-}1)$$

where $N\,\Delta x$ is the Grms level used in plotting.

Normal Distribution

$$f(x) = 1/S\sqrt{2\pi}\; e^{\left[-\frac{(x-M)^2}{2S^2}\right]}\,\Delta x \qquad (2.6\text{-}2)$$

M = Mean Grms Level

S = Standard Deviation

Δx = Step Size = 0.5 Grms

Rayleigh Distribution

$$f(x) = \frac{x}{\alpha^2} e^{-x^2/2\alpha^2} \Delta x \tag{2.6-3}$$

$$\Delta x = \text{Step Size} = 0.5 \text{ Grms}$$

The parameter α of the Rayleigh density can be the mean, standard deviation, and the first moment or second moment of the Rayleigh function (Reference 2). A more detailed study and discussion of the Rayleigh density and other classical functions will be included in future documentation.

Rayleigh (M)

$$\alpha = \text{Mean}$$

Rayleigh (SD)

$$\alpha = \text{Standard Deviation}$$

Rayleigh (MR)

$$\alpha = \frac{M}{\sqrt{\pi/2}} \qquad M = \text{Mean}$$

Rayleigh (TC)

$$\alpha = \frac{S}{\sqrt{2 - \pi/2}} \qquad S = \text{Standard Deviation}$$

Gamma Distribution

The Gamma distribution will be presented in more detail, since it appears to provide the most reasonable fit to the vibration data. It should be noted that the Gamma distribution contains two parameters related to both the mean and standard deviation. The four Rayleigh functions are one parameter systems and utilize the mean or standard deviation, but not both. The Gamma probability distribution is defined as

$$f(x) = \frac{\lambda}{\Gamma(r)} (\lambda x)^{r-1} e^{-\lambda x} \qquad x > 0 \tag{2.6-4}$$

where $\Gamma(r)$ is the Gamma, or generalized factorial function.

The parameter λ and r in terms of the mean and variance from Reference (3) are:

$$\bar{x} = \frac{r}{\lambda}, \quad \sigma^2 = r/\lambda^2 \tag{2.6-5}$$

Solving each equation for r

$$r = \bar{x}\lambda, \quad r = \sigma^2 \lambda^2 \tag{2.6-6}$$

or

$$\lambda^2 \sigma^2 = \lambda \bar{x} \tag{2.6-7}$$

$$\lambda = \bar{x}/\sigma^2 \tag{2.6-8}$$

From the first of Equation (2.6-5) and (2.6-8)

$$\bar{x} = \frac{r\sigma^2}{\bar{x}} \tag{2.6-9}$$

so

$$r = \bar{x}^2/\sigma^2 \tag{2.6-10}$$

Using Equations (2.6-4), (-8) and (-10)

$$f(x) = \frac{\bar{x}}{\sigma^2 \Gamma[\bar{x}^2/\sigma^2]} \left[\frac{\bar{x}\, x}{\sigma^2}\right]^{\left(\frac{\bar{x}^2}{\sigma^2} - 1\right)} e^{-\frac{\bar{x}\, x}{\sigma^2}} \tag{2.6-11}$$

Some important relationships of the Gamma function are:

$$\Gamma(n+1) = \int_0^\infty x^n e^{-x}\, dx, \text{ which leads to}$$

$$\Gamma(n) = (n-1)\, \Gamma(n-1) \tag{2.6-12}$$

$$\Gamma(n) = (n-1)\,!$$

$$\Gamma(n+1) = n\,!$$

Thus the definition as a generalized factorial function.

Therefore in terms of the mean Grms and standard deviation the Gamma density function is

$$f(x) = \frac{m}{s^2[m^2/s^2-1]!} * \frac{mx}{s^2}^{[(m^2/s^2)-1]} * e^{-\frac{(mx)}{s^2}} \Delta x \qquad (2.6\text{-}13)$$

m	=	Mean Grms Level
s	=	Standard Deviation
Δ x	=	Step Size = 0.5

Although the Gamma distribution appears to provide a reasonable fit to the data, some additional improvements should be investigated. These include a change in the class interval width, unequal class intervals and maybe some type of truncated Gamma or other classical function to account for the low synchronous values approaching the noise floor of the instrumentation. It may be noted F(x) and f(x) are not the continuous form of the cumulative probability function and probability density function, but represent percentiles within discrete class intervals. This formulation permits direct comparison between classical function approximations and discrete frequency distributions representing empirical measurement characteristics.

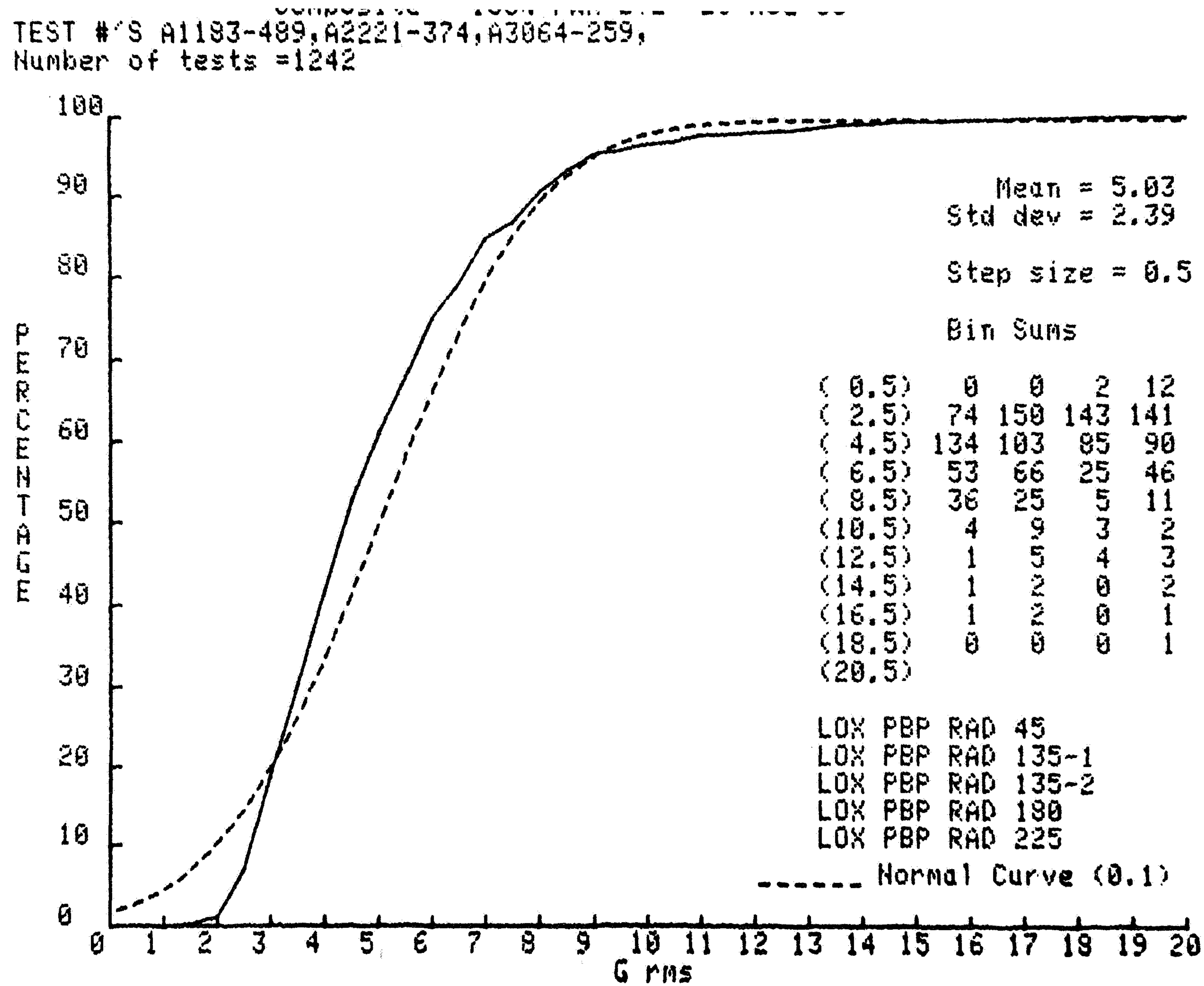

Figure 9. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Normal Overlay

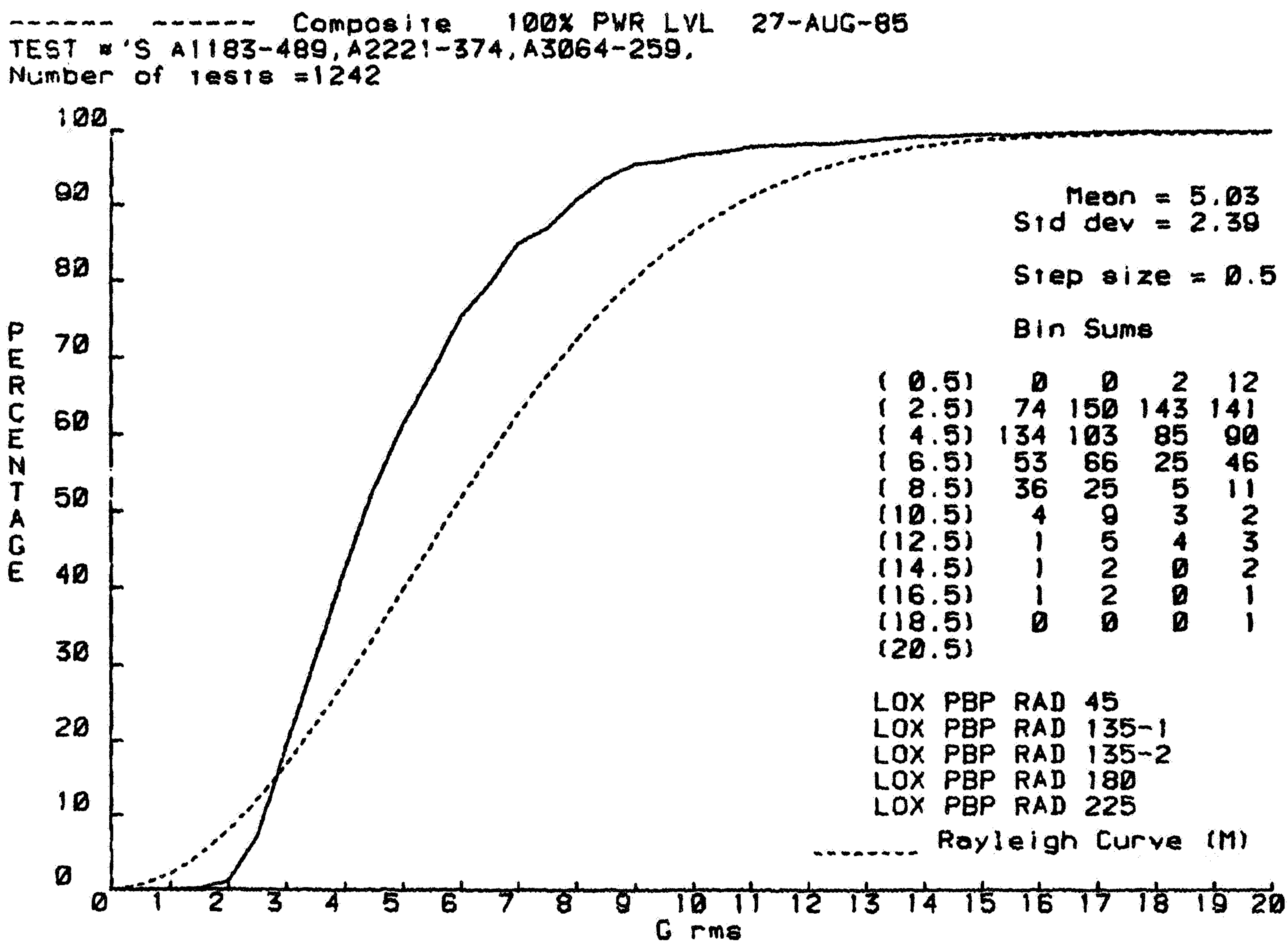

Figure 10. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Rayleigh (M) Overlay

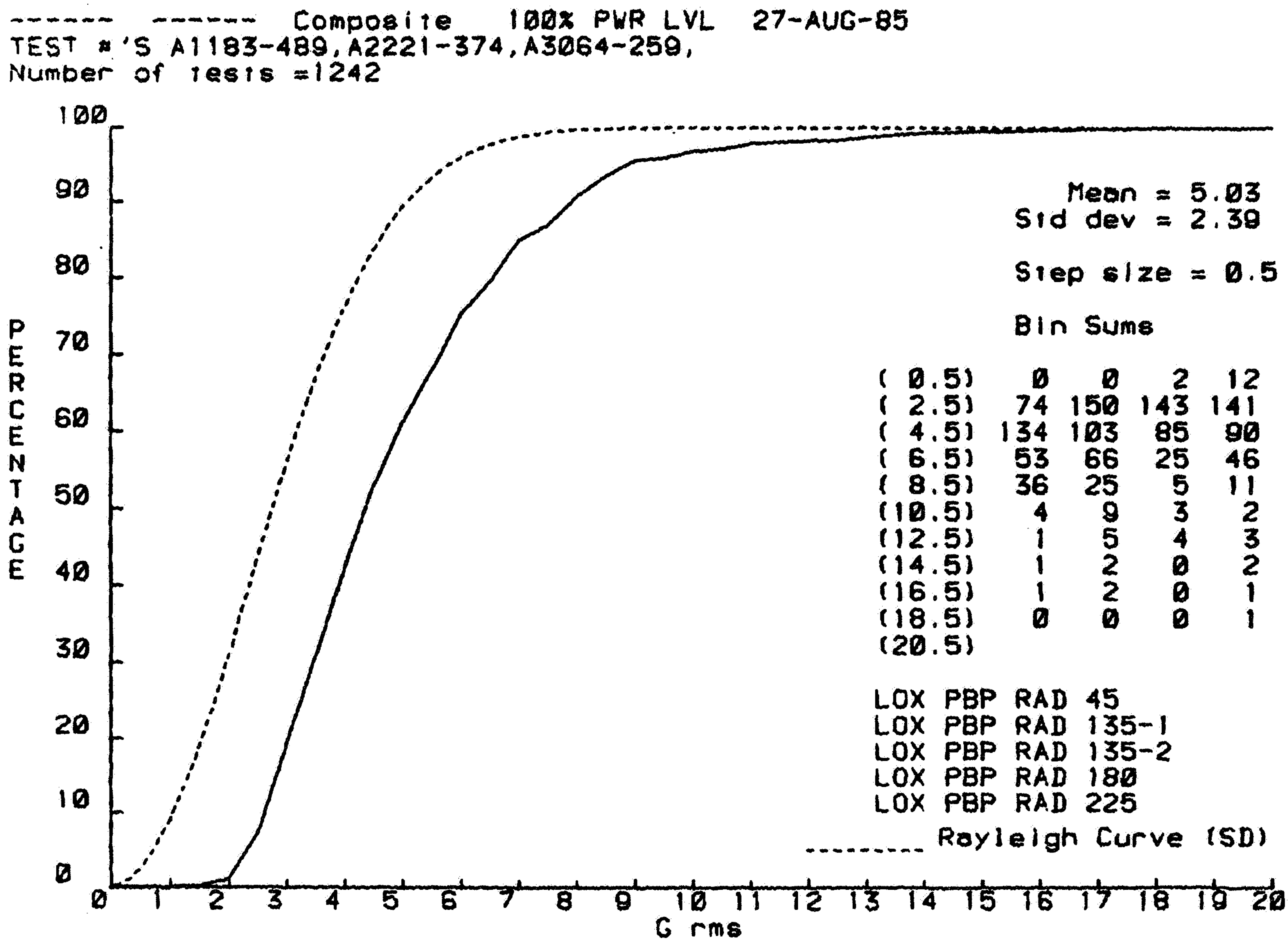

Figure 11. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Rayleigh (SD) Overlay

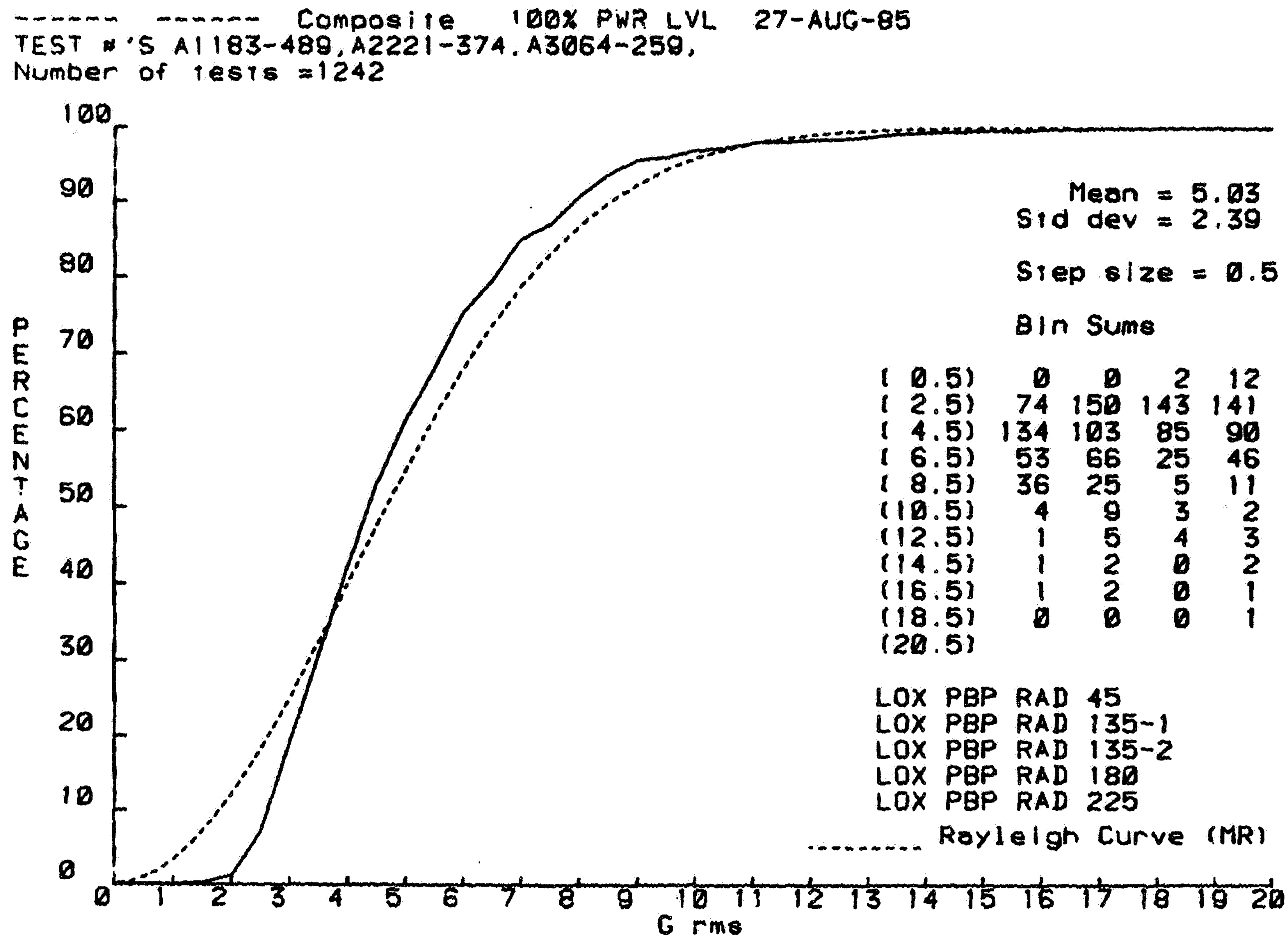

Figure 12. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Rayleigh (MR) Overlay

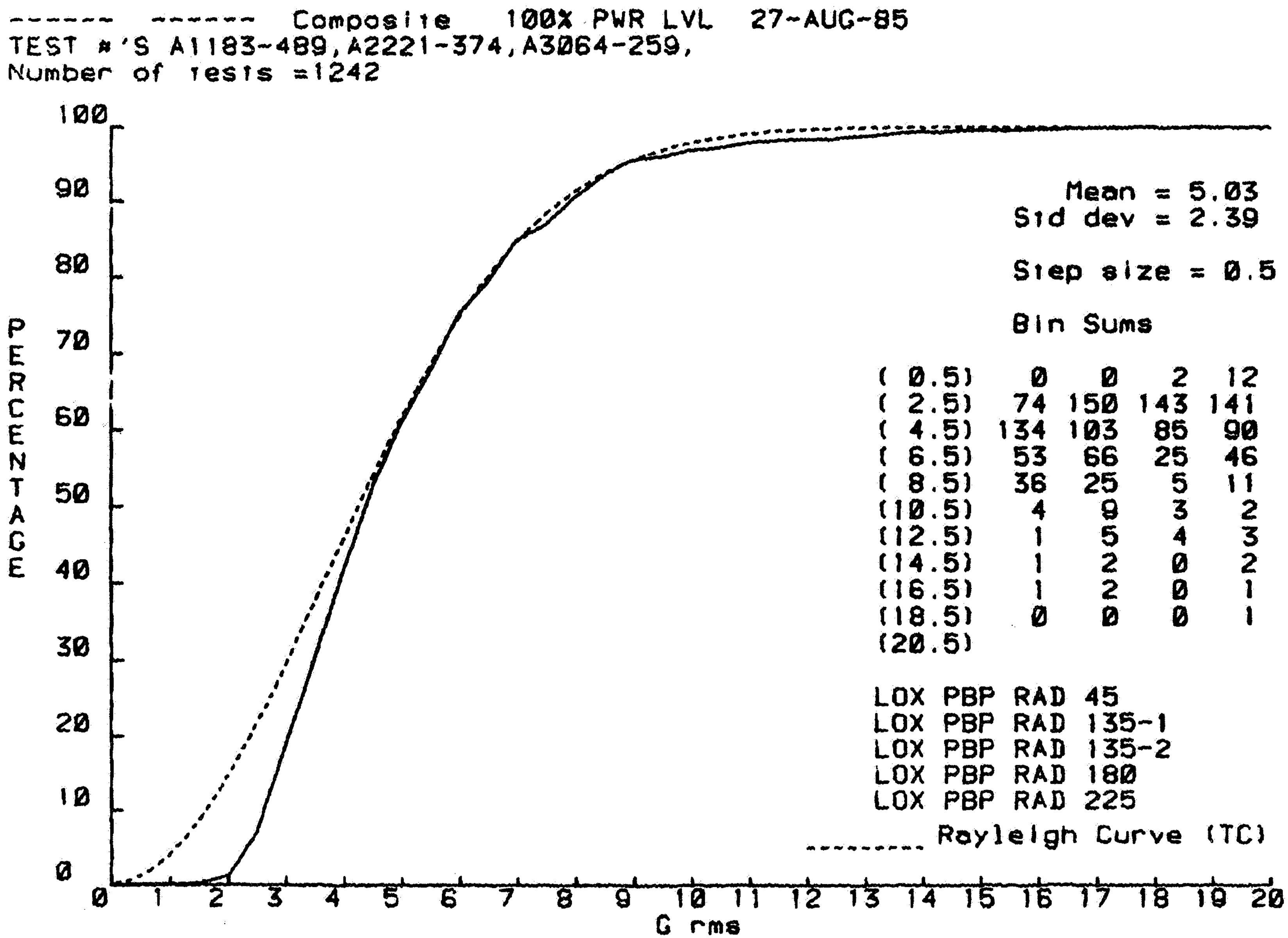

Figure 13. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Rayleigh (TC) Overlay

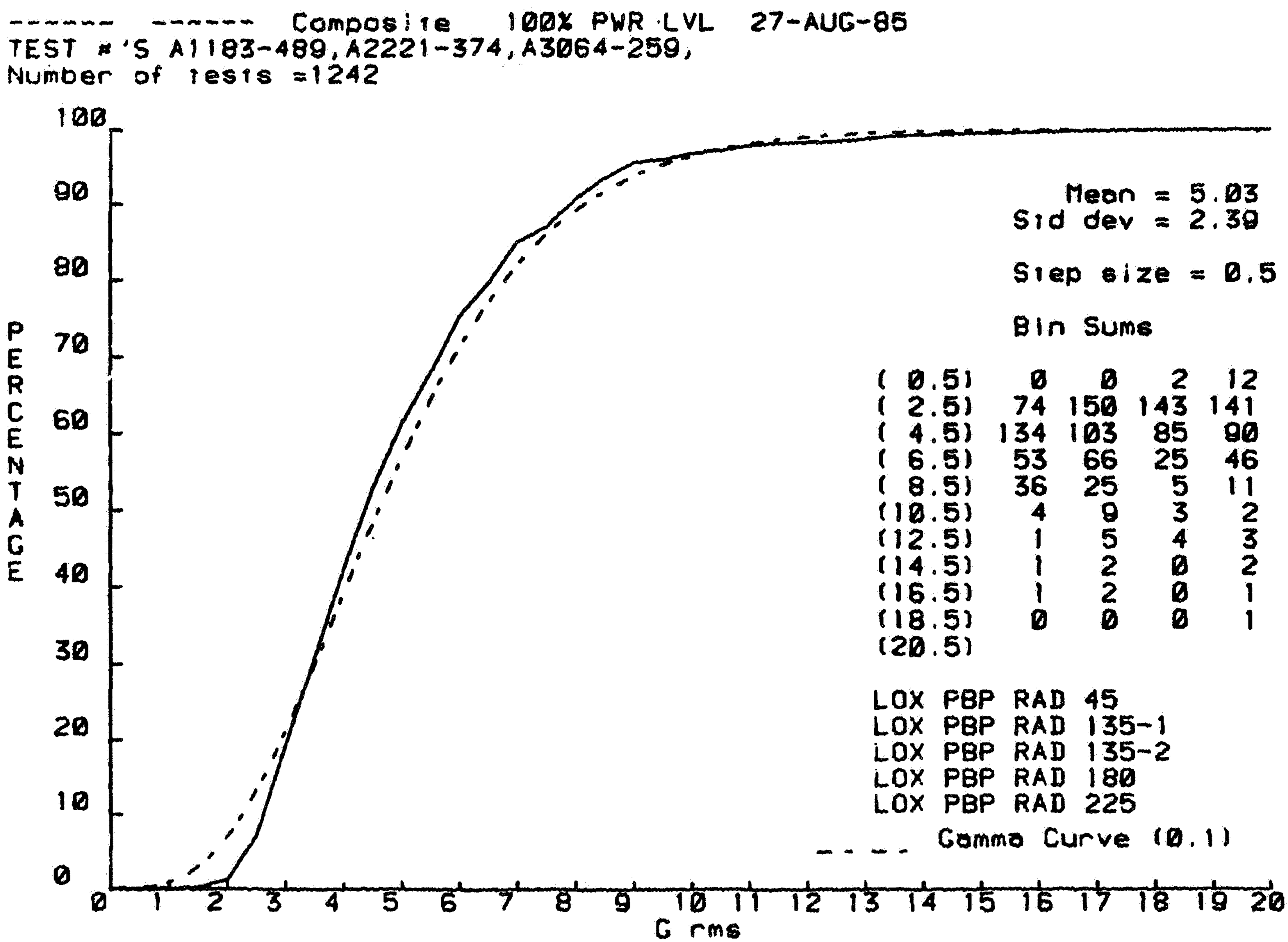

Figure 14. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Composite) Gamma Overlay

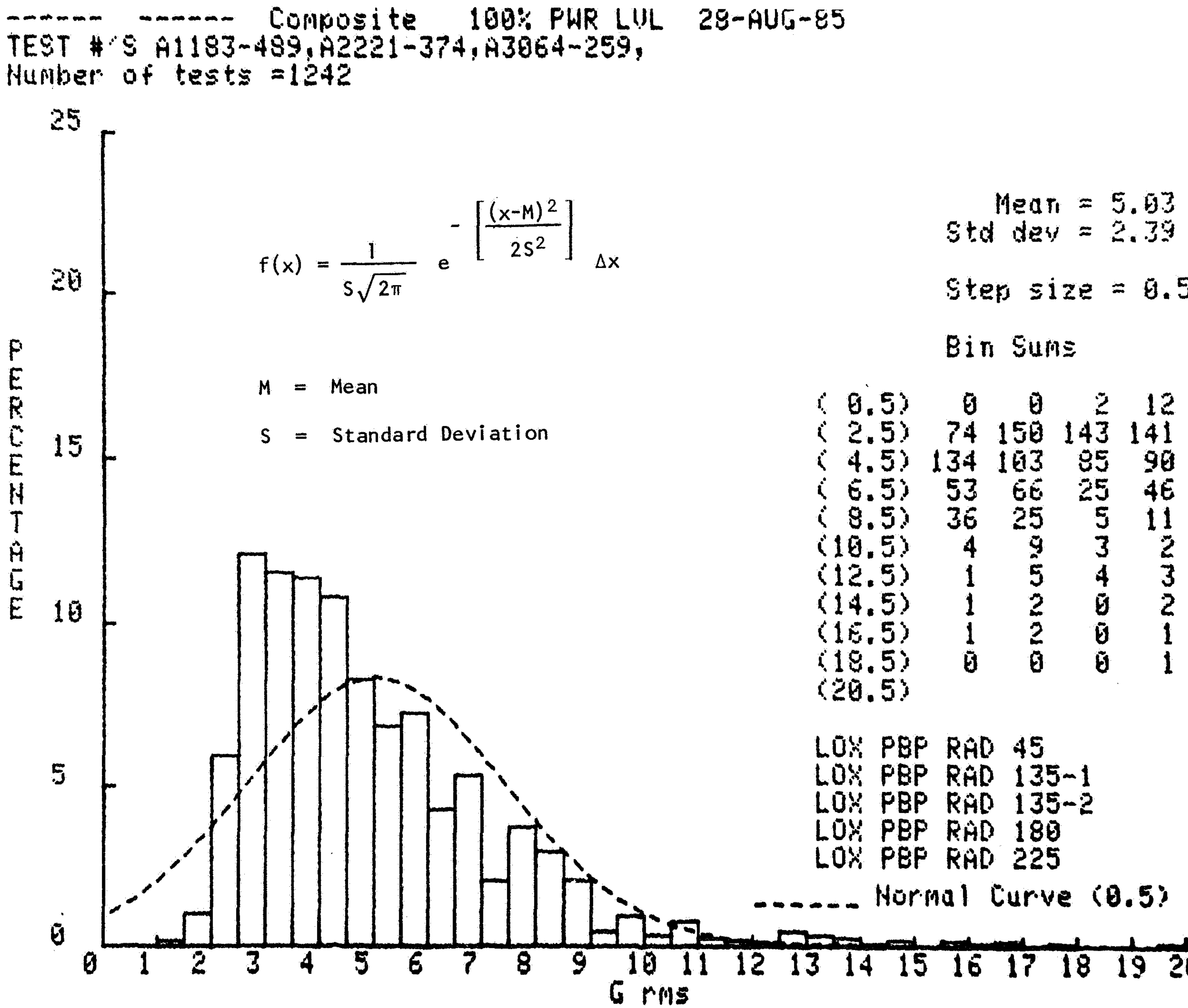

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Figure 15. Probability Density (LOX PBP RAD, Static Firing, Composite) Normal Overlay

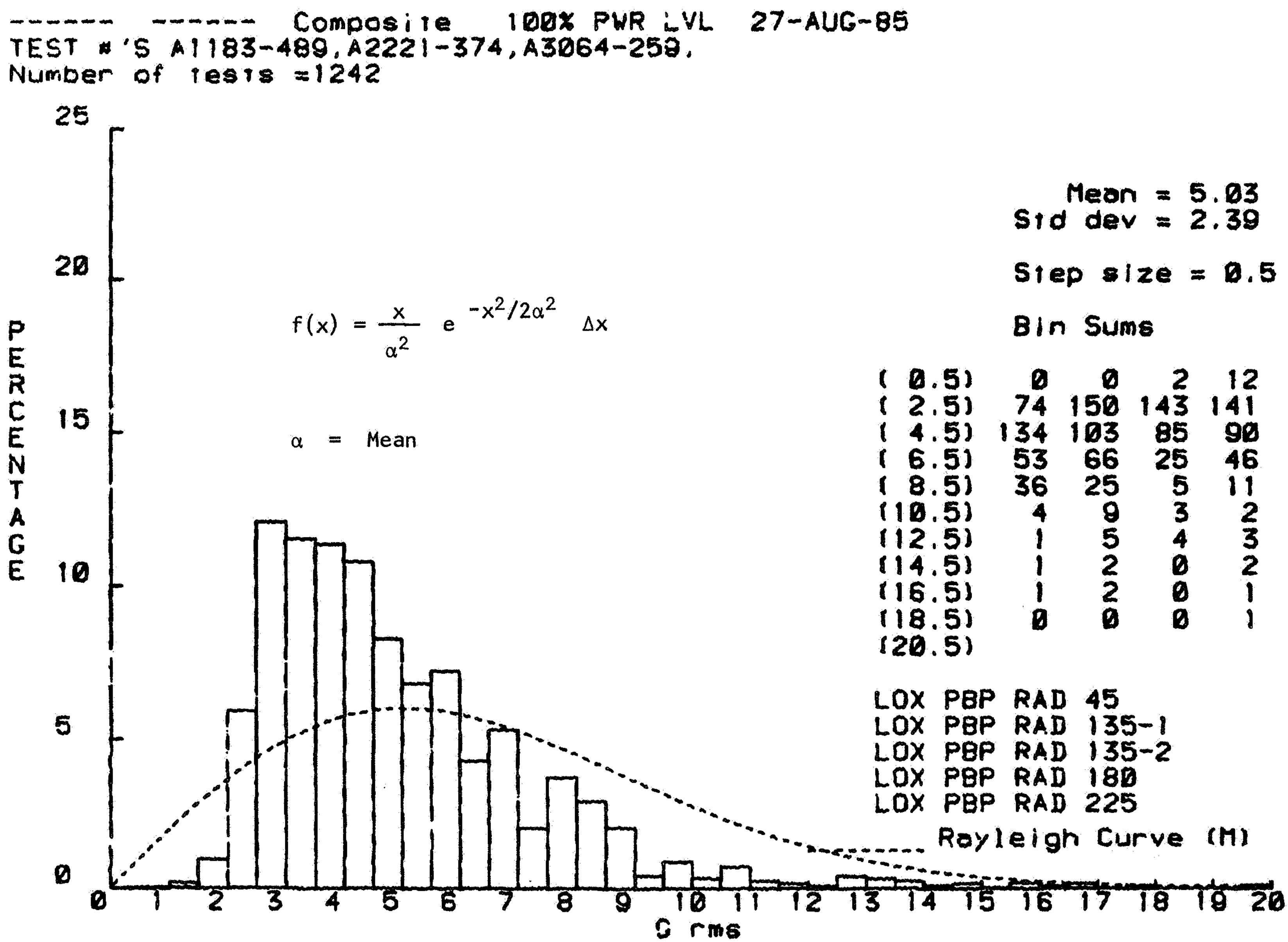

Figure 16. Probability Density (LOX PBP RAD, Static Firing, Composite) Rayleigh (M) Overlay

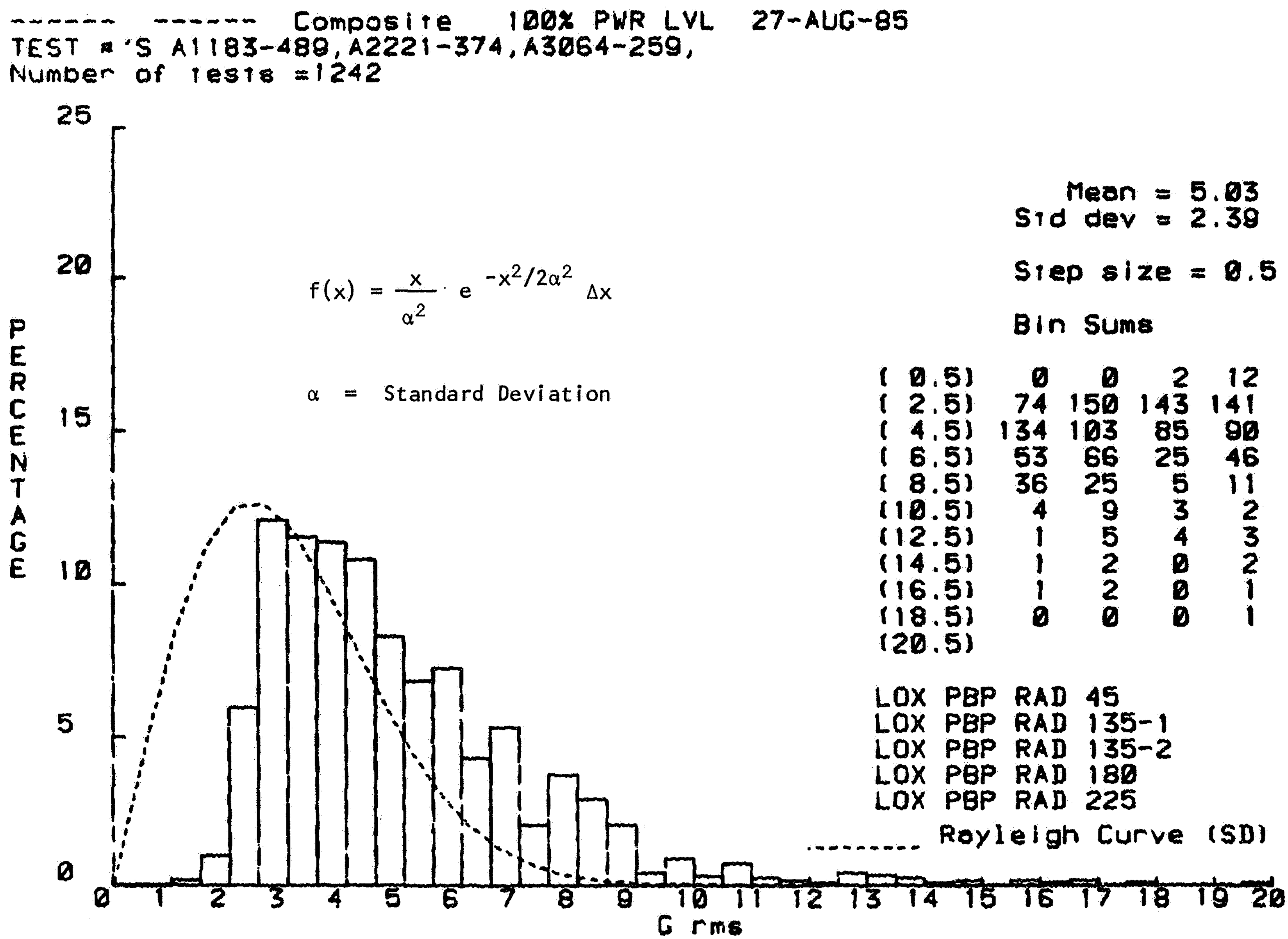

Figure 17. Probability Density (LOX PBP RAD, Static Firing, Composite) Rayleigh (SD) Overlay

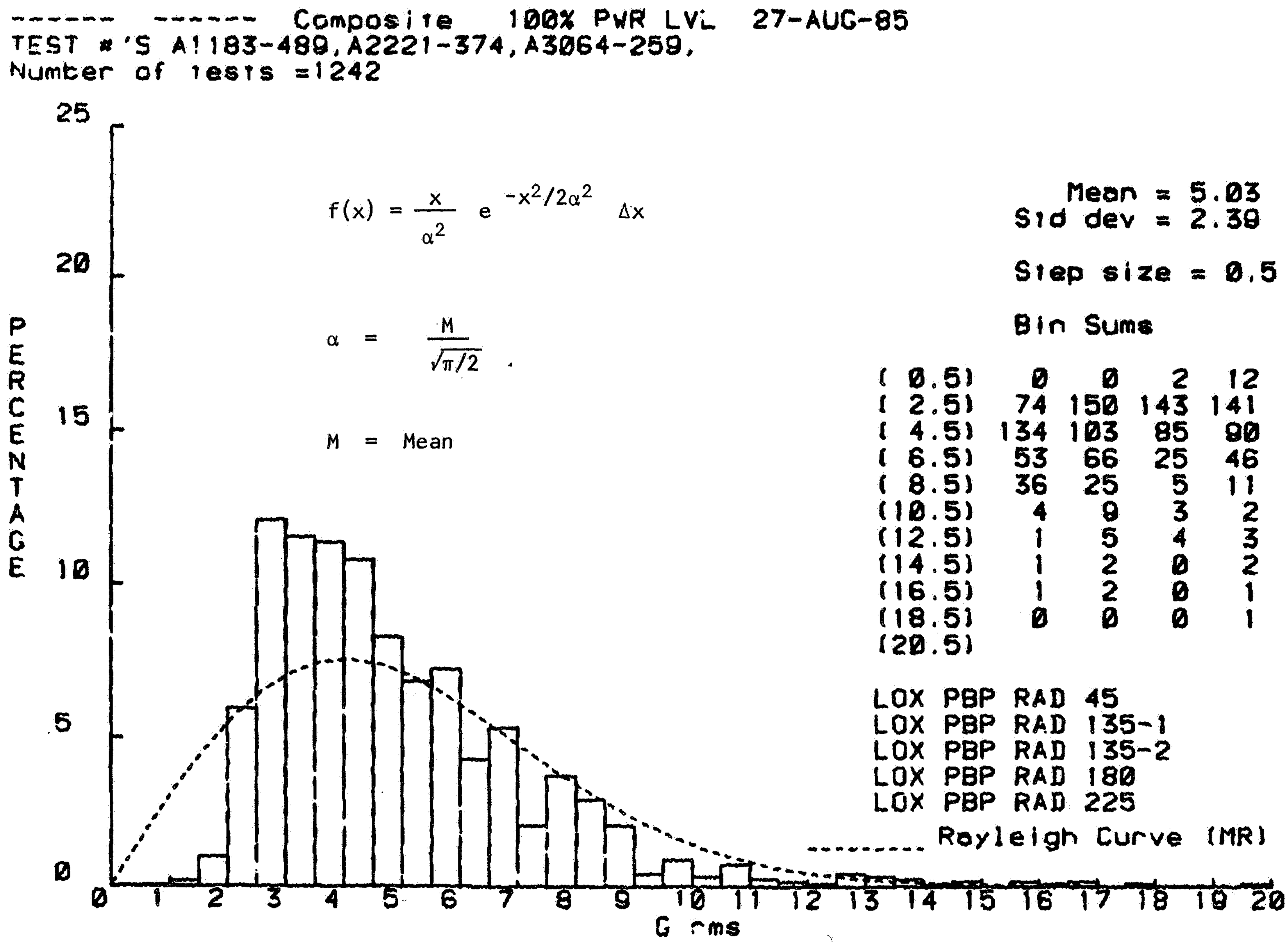

Figure 18. Probability Density (LOX PBP RAD, Static Firing, Composite) Rayleigh (MR) Overlay

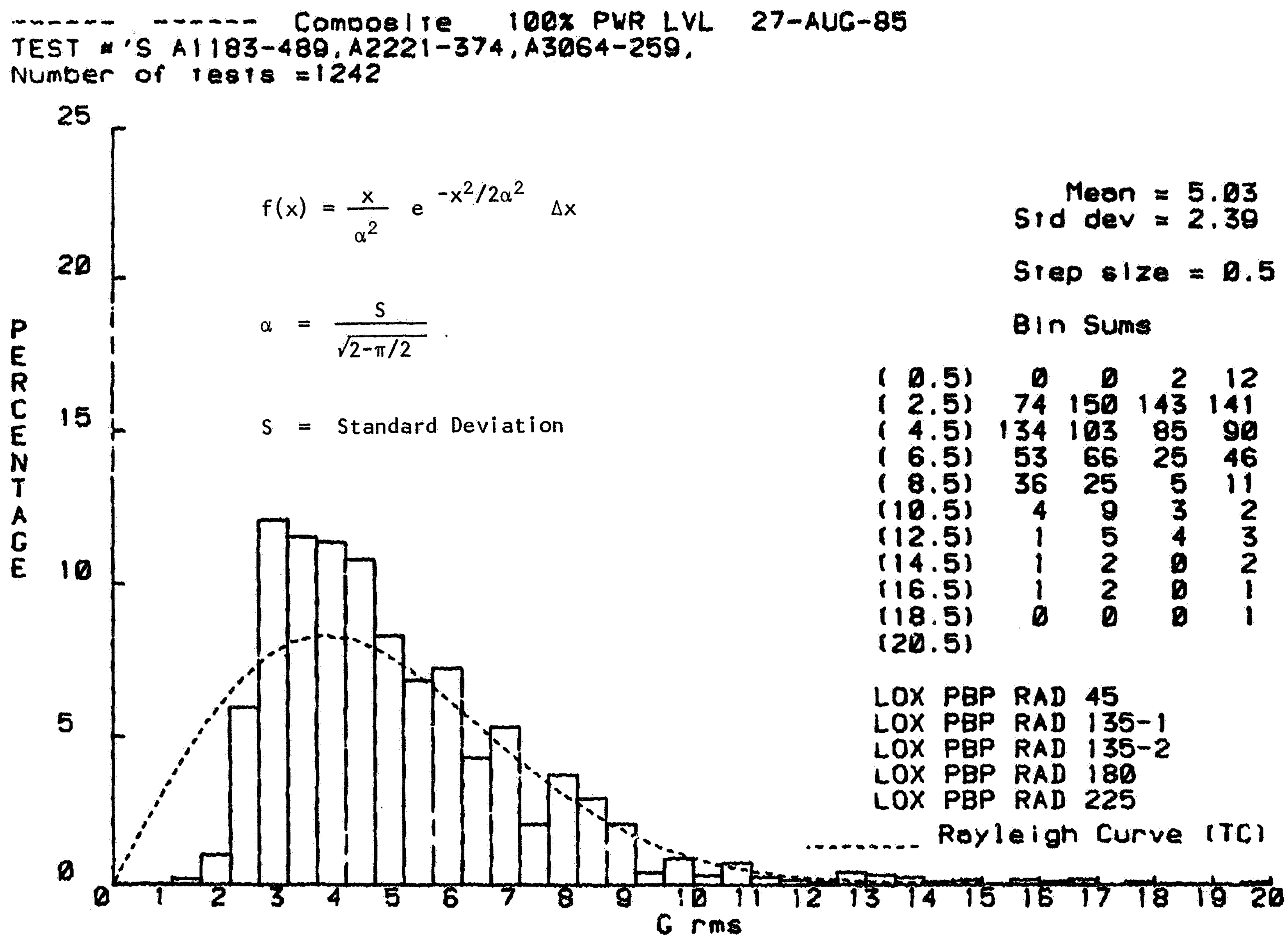

Figure 19. Probability Density (LOX PBP RAD, Static Firing, Composite) Rayleigh (TC) Overlay

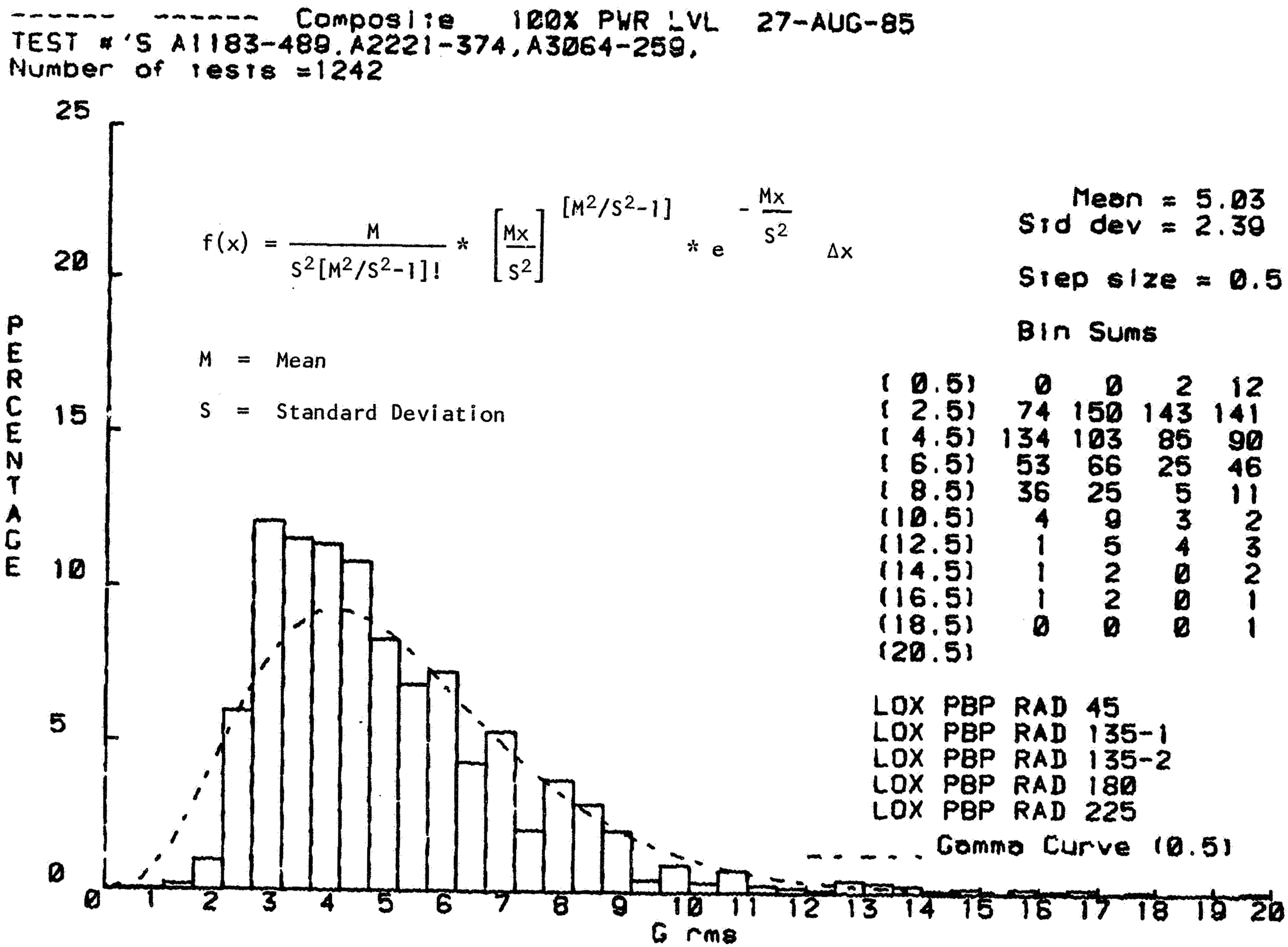

Figure 20. Probability Distribution (LOX PBP RAD, Static Firing, Composite) Gamma Overlay

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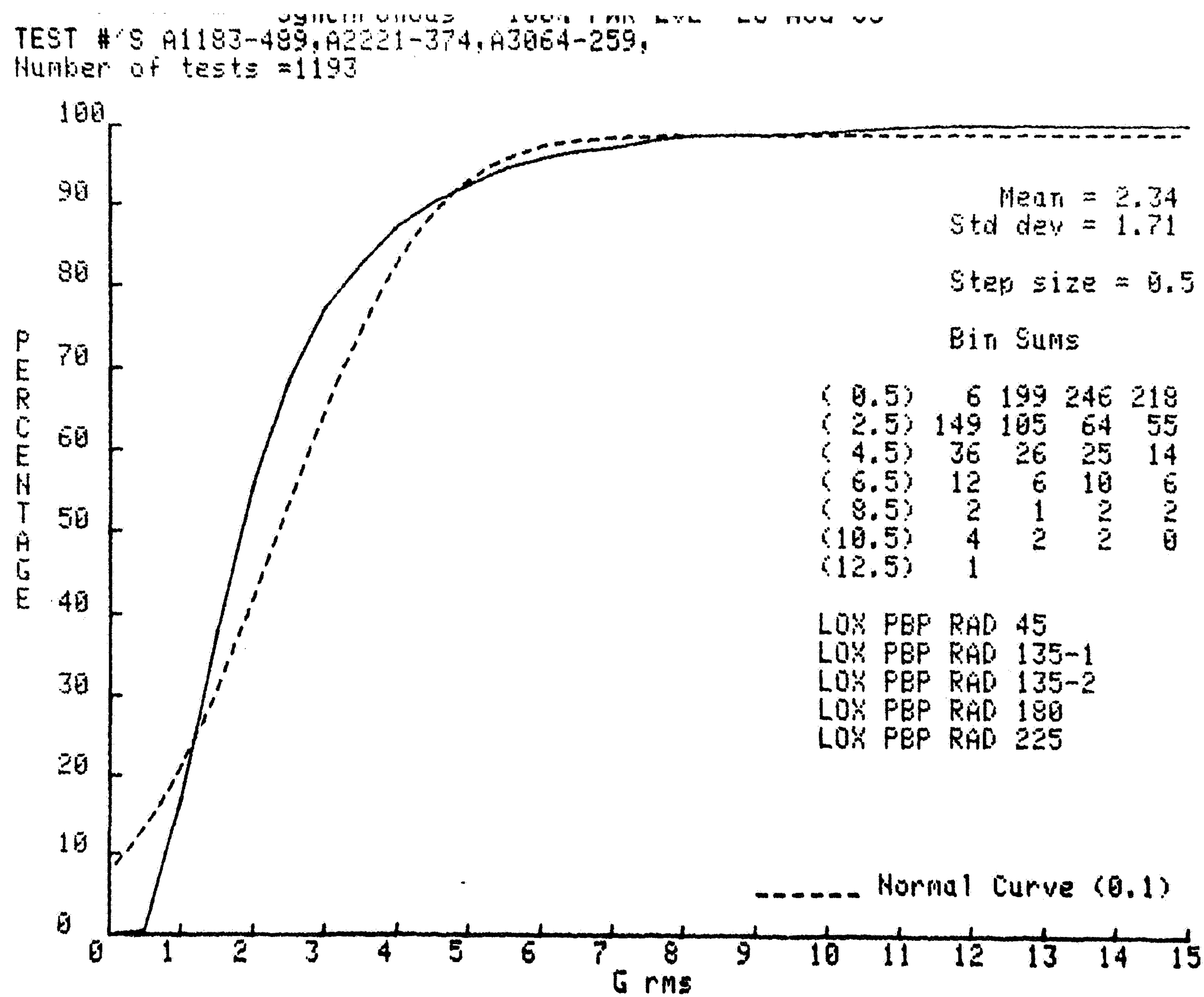

Figure 21. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Normal Overlay

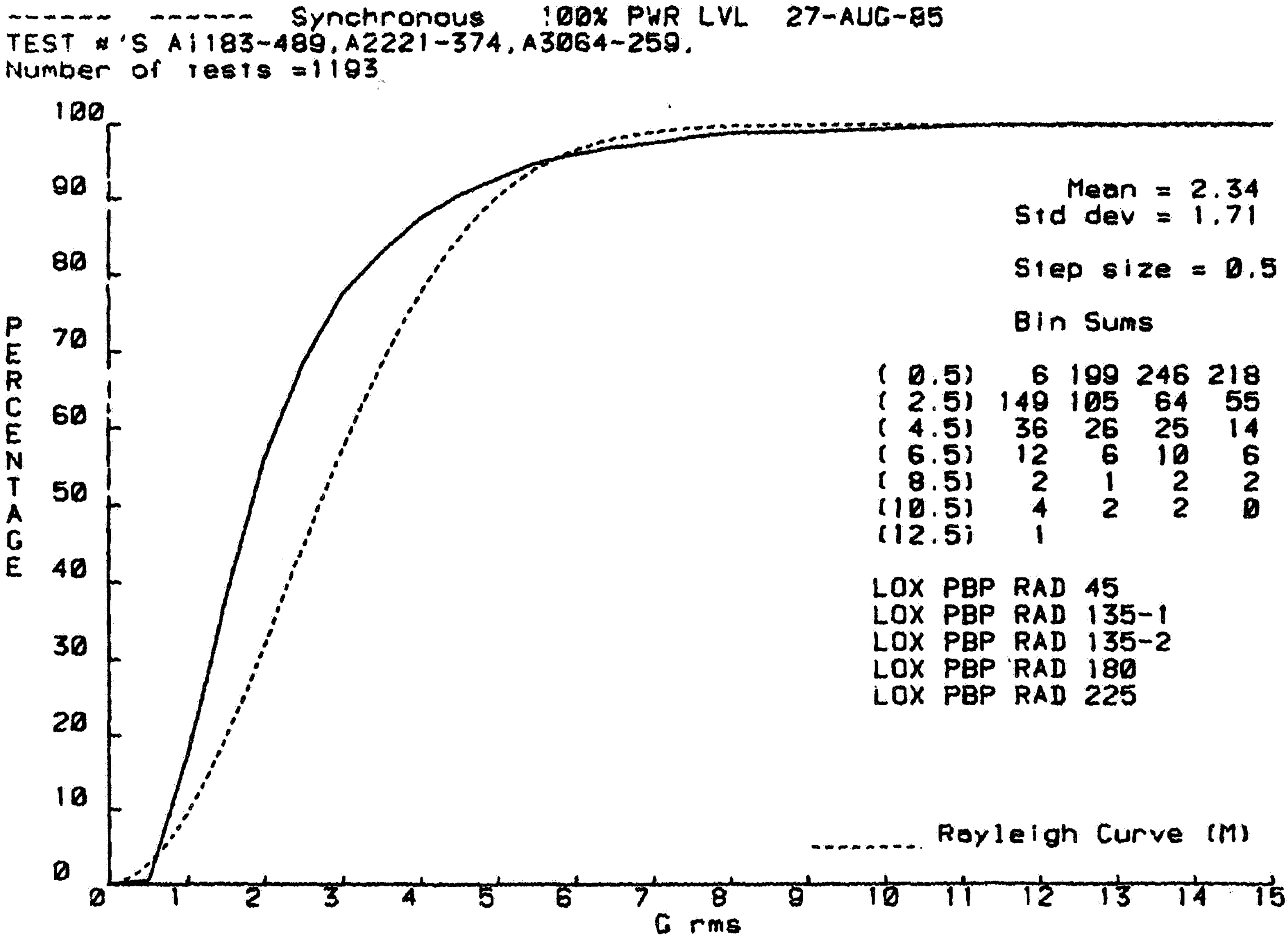

Figure 22. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (M) Overlay

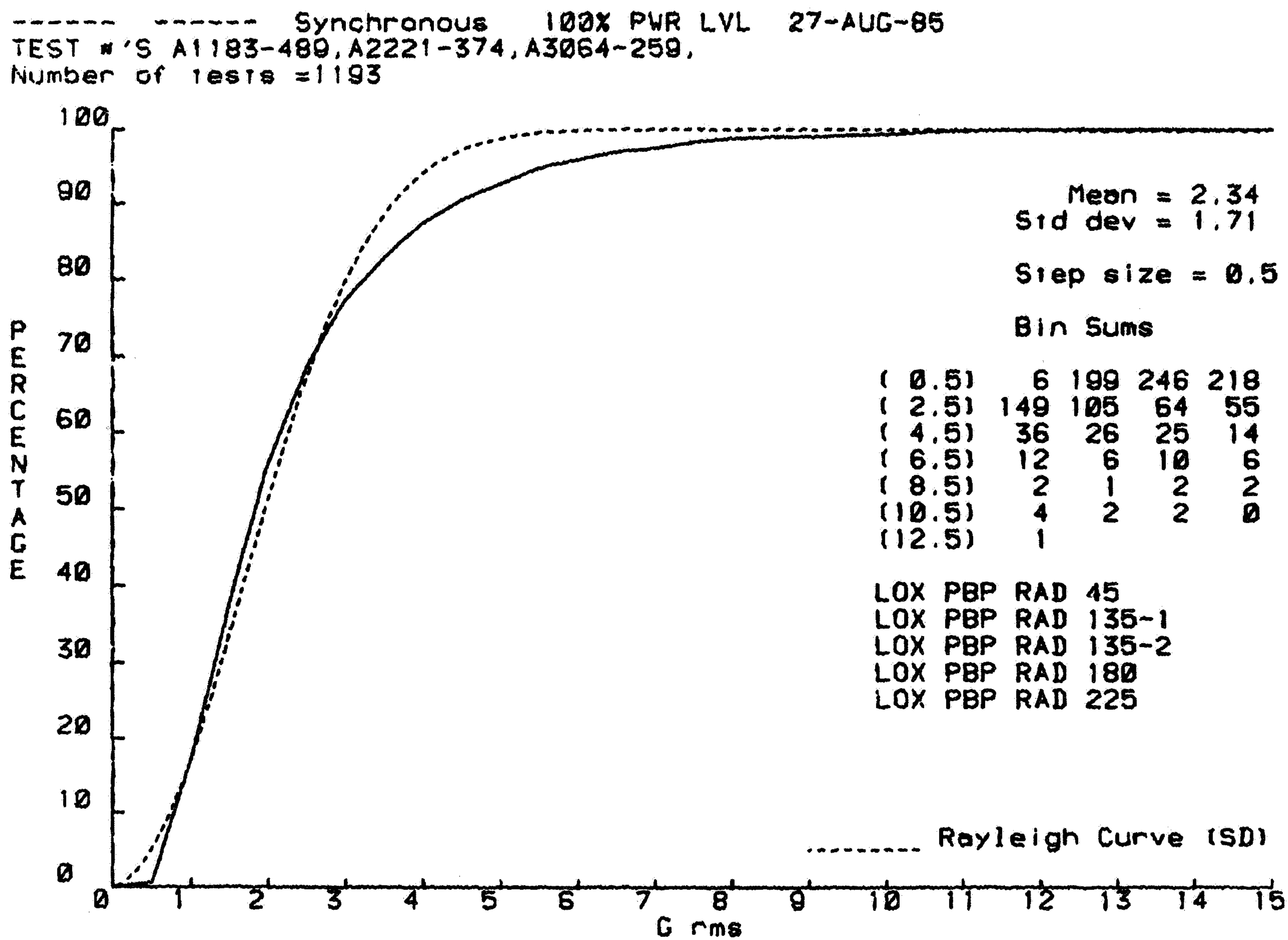

Figure 23. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (SD) Overlay

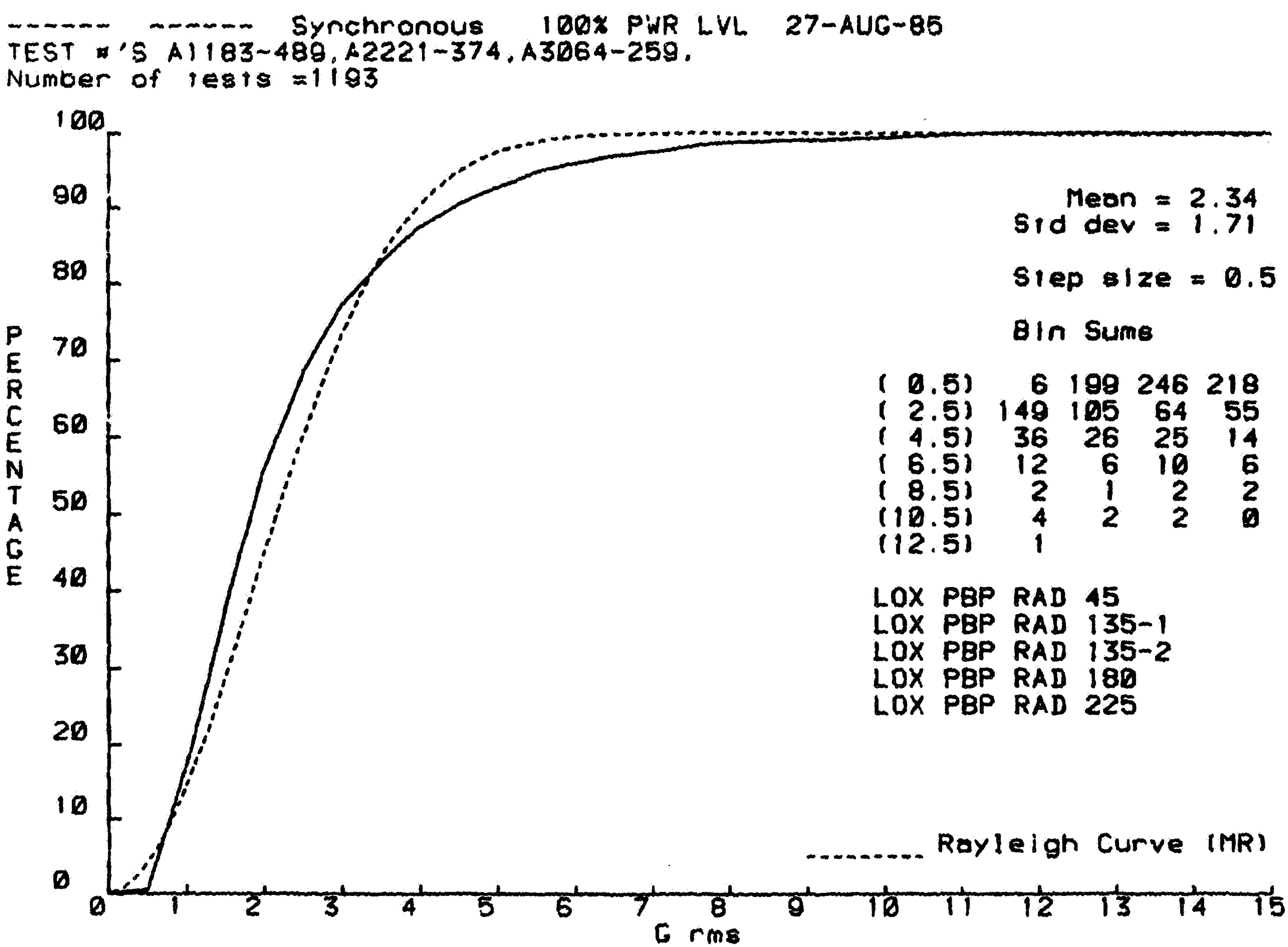

Figure 24. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (MR) Overlay

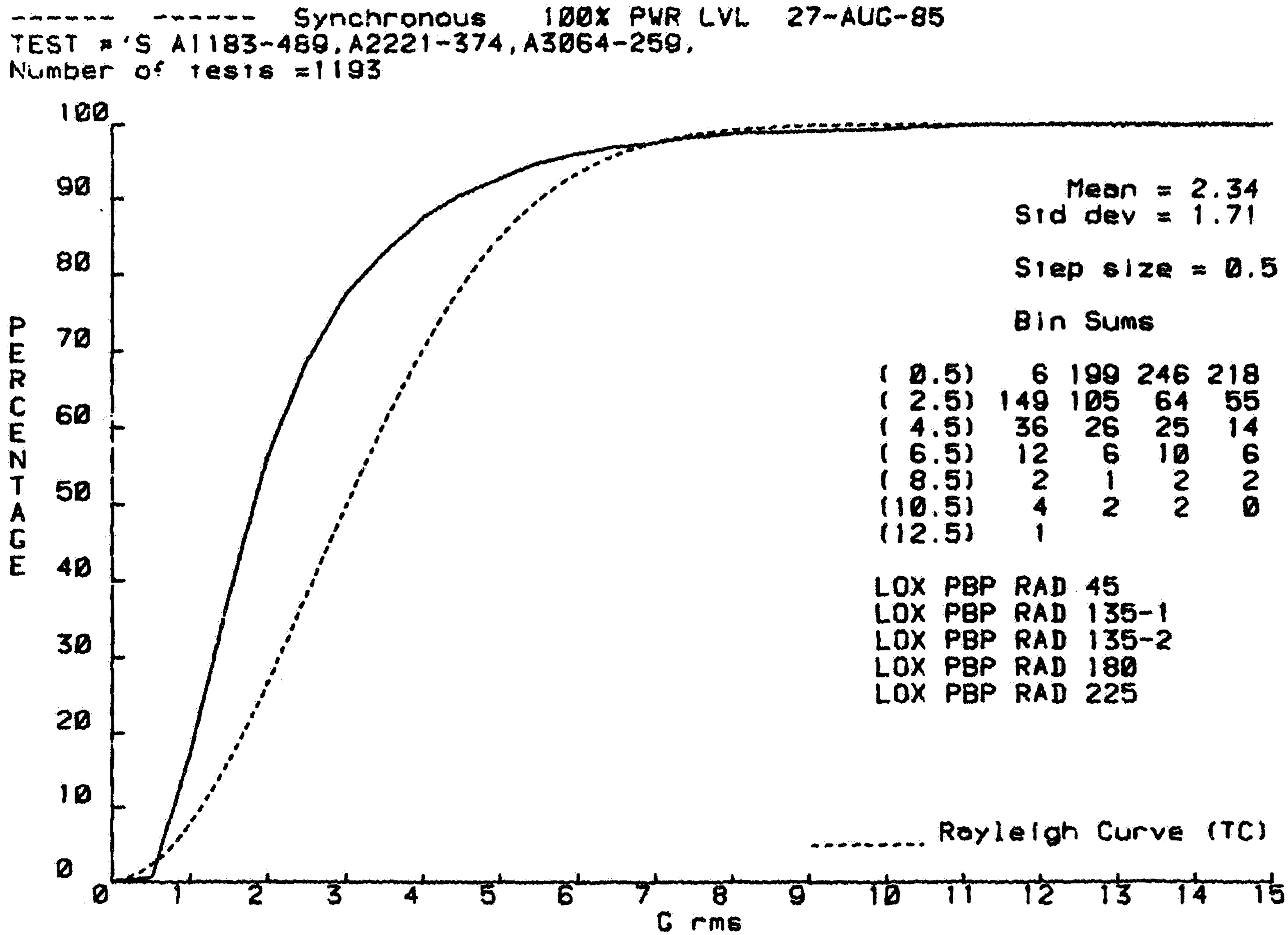

Figure 25. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (TC) Overlay

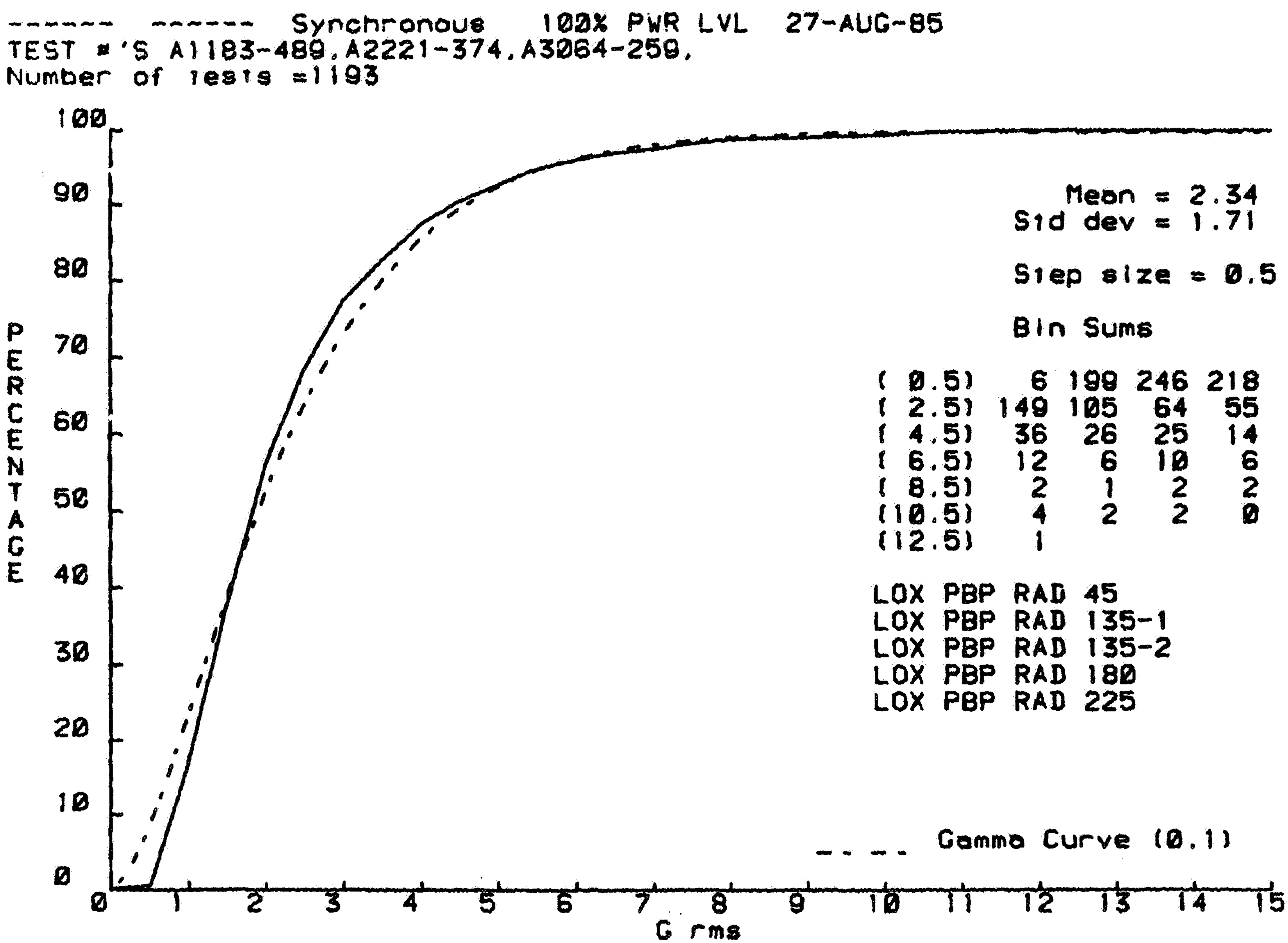

Figure 26. Cumulative Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Gamma Overlay

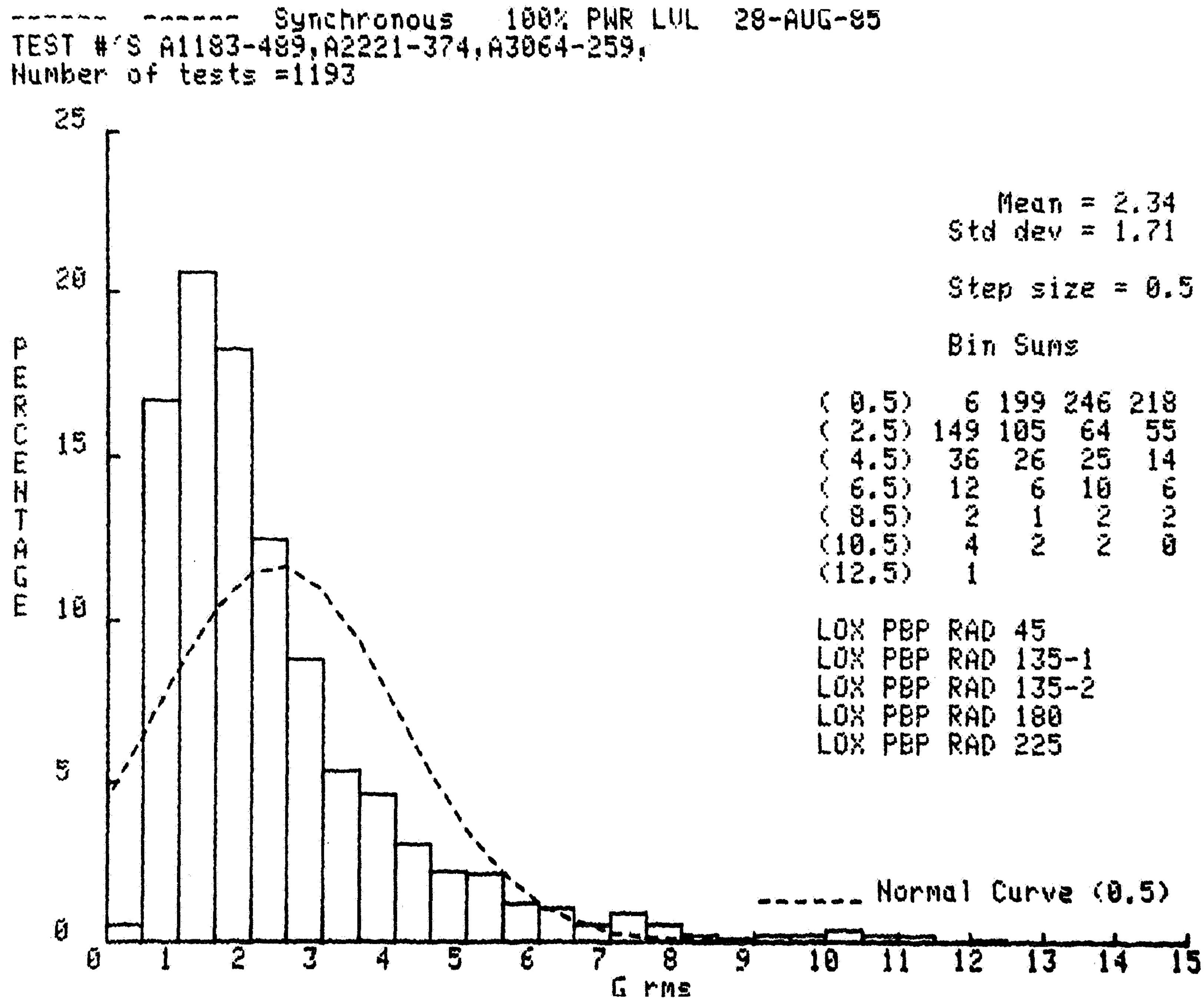

Figure 27. Probability Density (LOX PBP RAD, Static Firing, Synchronous) Normal Overlay

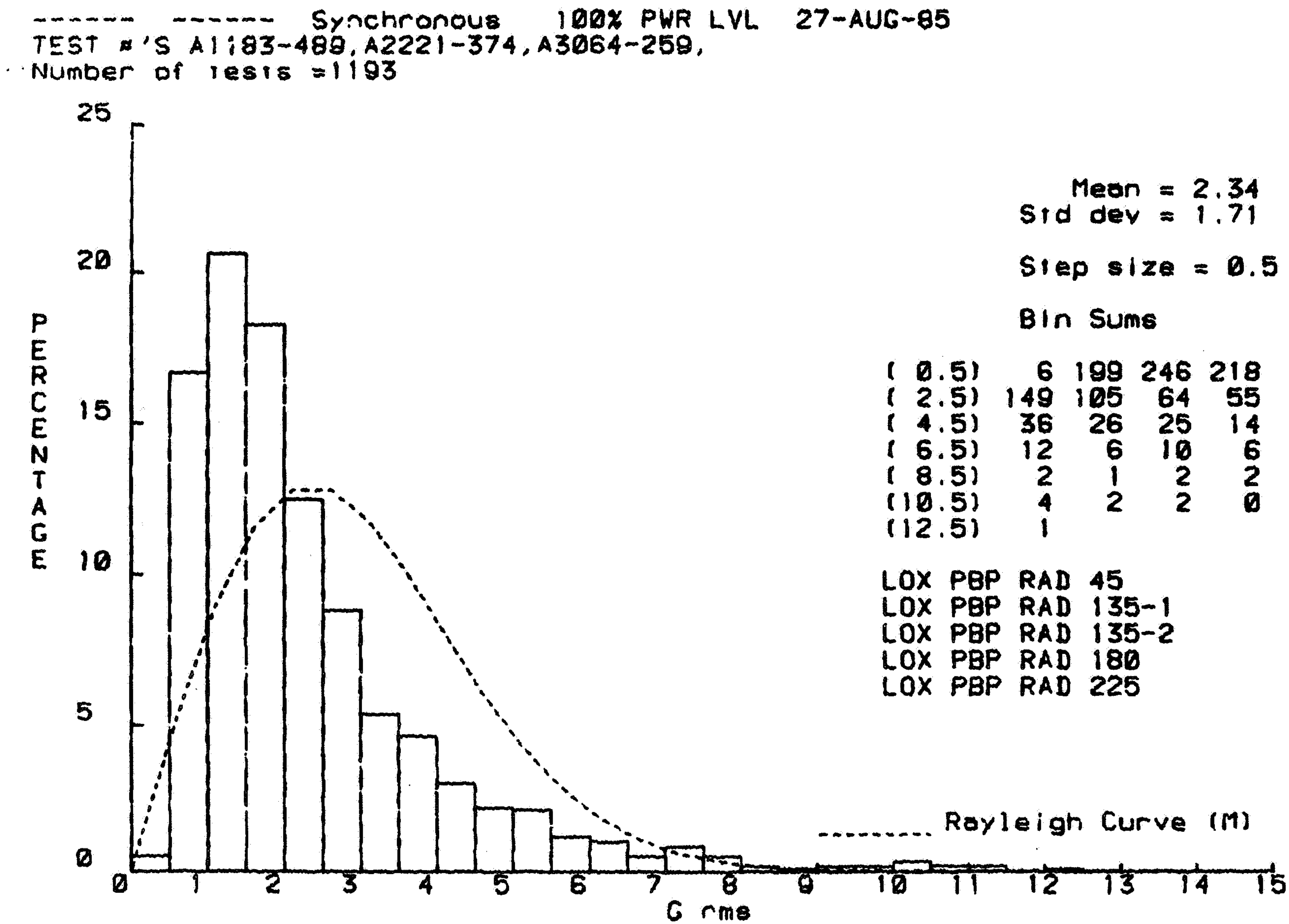

Figure 28. Probability Density (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (M) Overlay

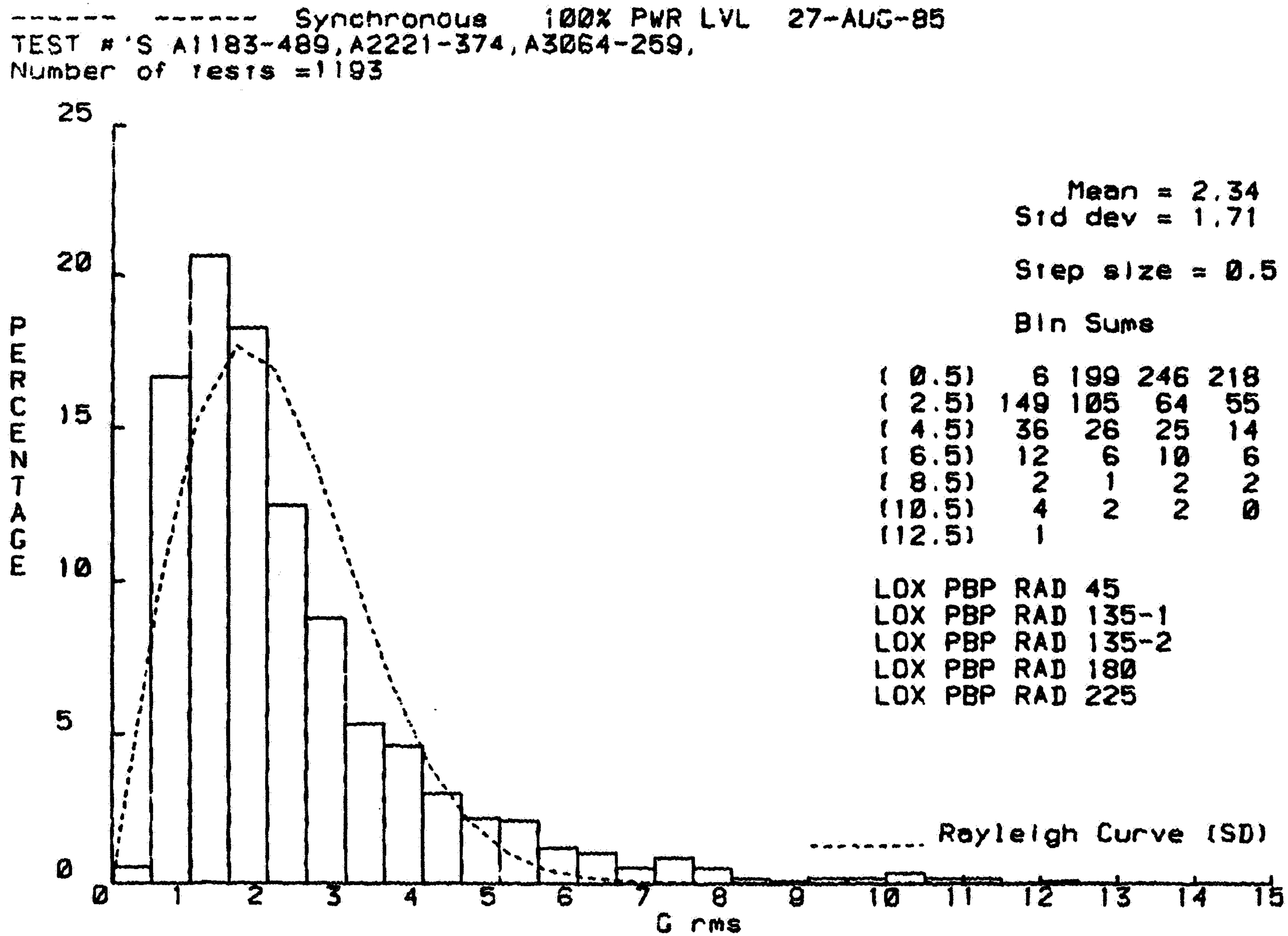

Figure 29. Probability Density (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (SD) Overlay

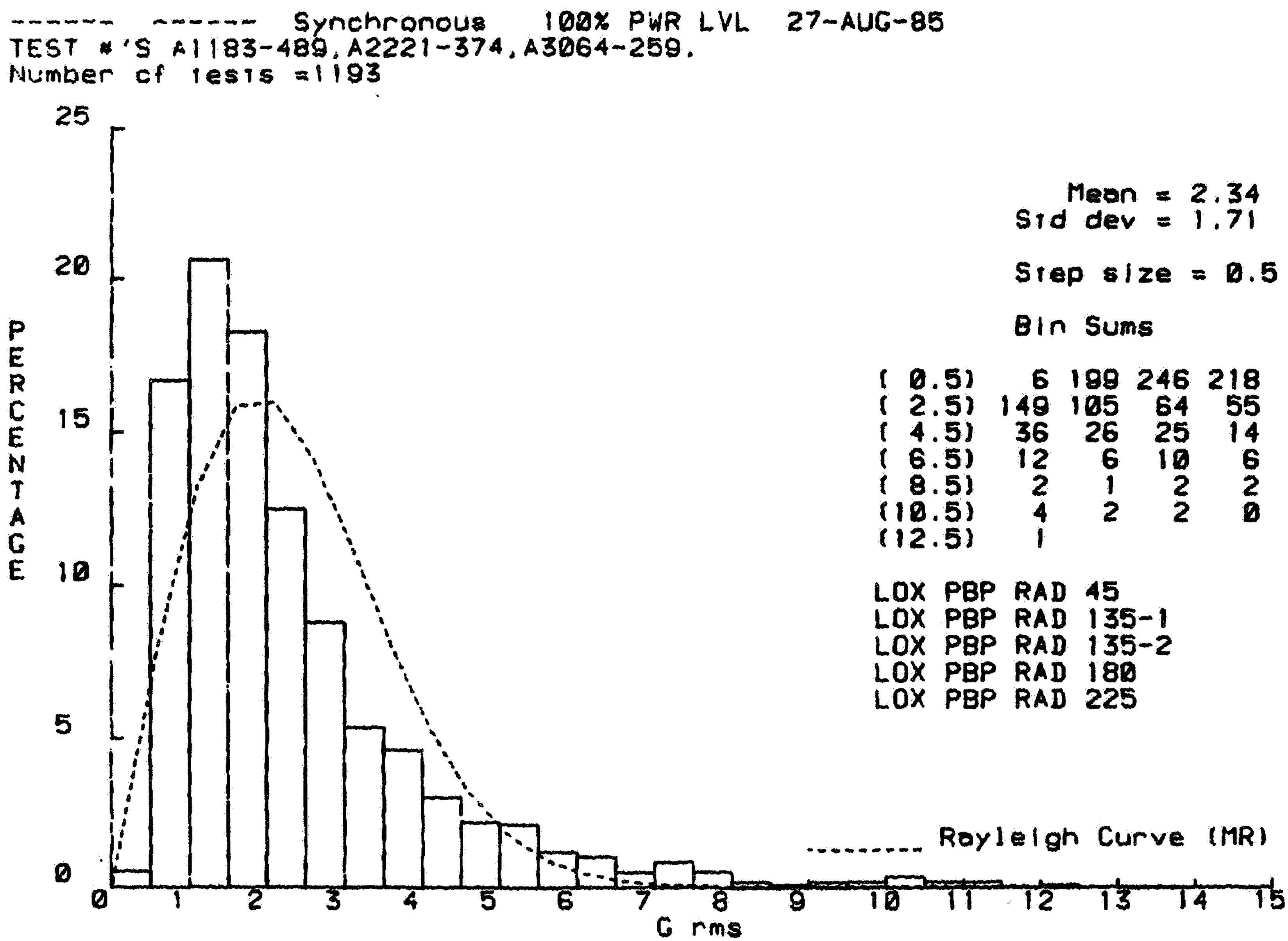

Figure 30. Probability Density (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (MR) Overlay

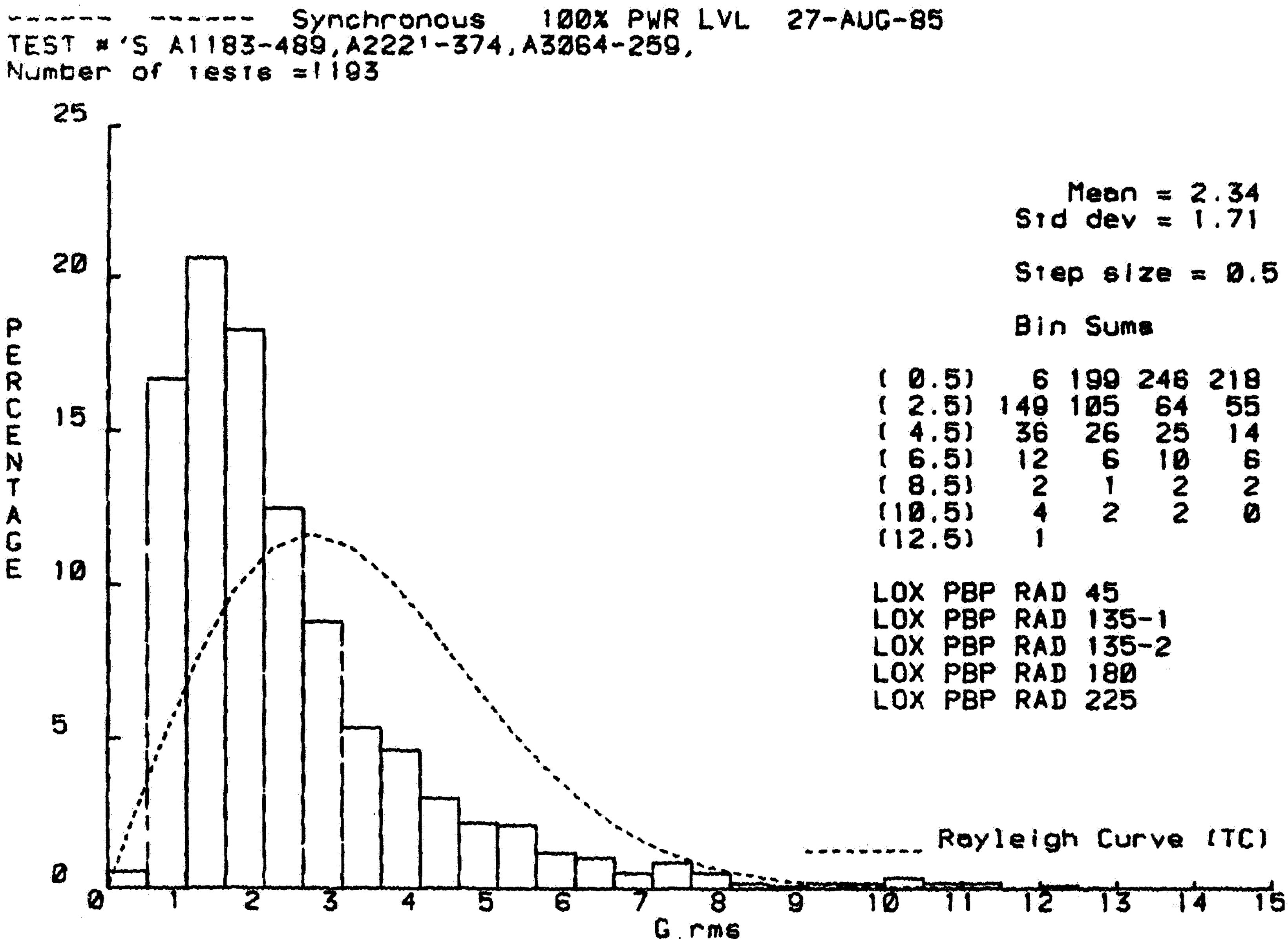

Figure 31. Probability Density (LOX PBP RAD, Static Firing, Synchronous) Rayleigh (TC) Overlay

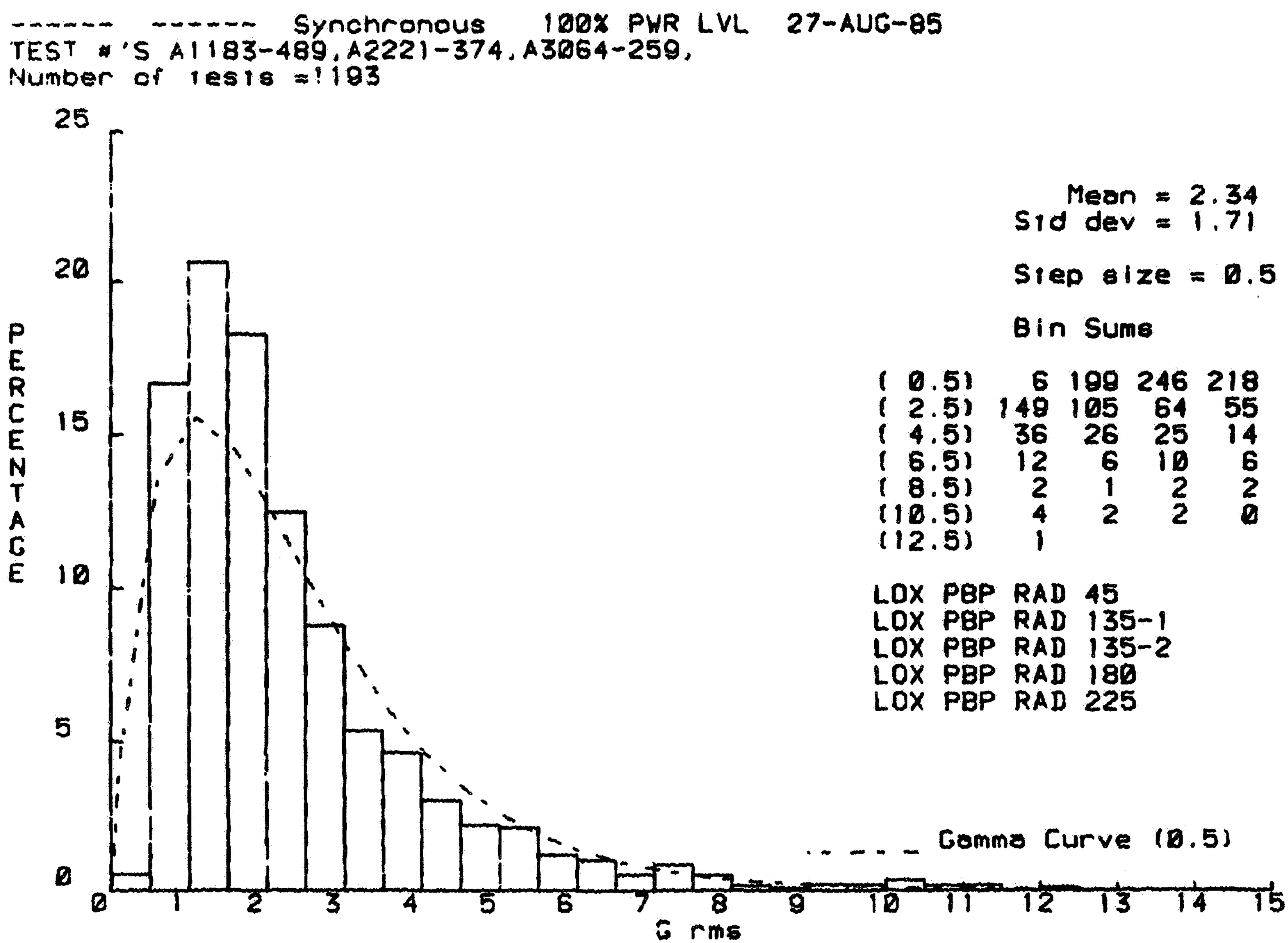

Figure 32. Probability Distribution (LOX PBP RAD, Static Firing, Synchronous) Gamma Overlay

2.7 Sort Routine for Probability Density Function

A variation of the following quick sort routine is used in the MSFC Diagnostic Data Base Program to calculate the density functions. The procedure follows Reference 4. This method requires only one data pass and therefore is basically the fastest most simple routine available.

Consider the N data values for the composite, synchronous etc. for each measurement. The probability density function can be estimated by

$$\hat{f}(x) = \frac{N_x}{N\,W}$$

where W is a narrow interval centered at x and N_x is the number of data values which fall within the range $x \pm W/2$. A general procedure to estimate $\hat{f}(x)$ can be obtained digitally by dividing the full range of x into an appropriate number of equal width class intervals. Tabulate the number of data values in each class interval, and divide by the product of the class interval width W and the sample size N. The estimate $\hat{f}(x)$ is not unique since it is dependent upon the number of class intervals and their width selected for the analysis. Equal class intervals of 0.5 Grms were used in the MSFC Diagnostic Data Bank Program. The number of class intervals is equal to twice the maximum value of the plot with the data plotted at x rather than $x \pm W/2$. This is not in strict accordance with the above definition, but for data interpretation the plots show the percentage of data values less than or equal to x, where x is the Grms value.

A general procedure for evaluation is as follows. Let K define the number of class intervals selected to cover the entire range of the data values from a_o to b_m. Then the width of each interval is given by

$$W = \frac{b_m - a_o}{K}$$

and the end point of the ith interval is

$$n_i = a_o + i\,W \qquad i = 0, 1, 2, \ldots K$$

where $n_o = a_o$ and $n_k = b_m$. The bin numbers will now be defined as a sequence of K+2 numbers $[N_i]$, i = 0, 1, 2, . . . K+1, by the conditions

$$
\begin{aligned}
N_o &= [\text{number of } x \text{ such that } x \le n_o] \\
N_1 &= [\text{number of } x \text{ such that } n_o < x \le n_1] \\
&\ \vdots \\
N_i &= [\text{number of } x \text{ such that } n_{i-1} < x \le n_i] \\
&\ \vdots \\
N_k &= [\text{number of } x \text{ such that } n_{k-1} < x \le n_k] \\
N_{k+1} &= [\text{number of } x \text{ such that } x > n_k]
\end{aligned}
$$

This procedure will sort out the N data values of x so that the bin number sequence $[N_i]$ satisfies

$$N = \sum_{i=0}^{K+1} N_i$$

A quick one pass method of sorting on a digital computer is to evaluate each value x_n; n=1, 2, . . . , N in turn as follows.

a. if $x_n \le a_o$, add the integer one to N_o.

b. If $a_o < x_n \le b_m$, compute $I = \dfrac{x_n - a_o}{W}$

then select i as the largest integer less than or equal to I, and add the integer one to N_i.

c. If $x_n > b_m$, add the integer one to N_{k+1}.

The four output forms are histogram, percentage of data in each class interval, probability density estimate and probability distribution estimate.

The histogram is simply N_i without changes

$$H_i = N_i \qquad \text{Histogram}$$

where H_i is the number of data values in each class interval.

The second output is the sample percentage of data in each class interval defined for i = 0, 1, 2, . . . K+1 by

$$\hat{F}_i \% = \frac{N_i}{N} \times 100 \qquad \text{Percentage of Data}$$

The third output is the probability density estimate defined at the midpoints of the K class intervals in $[a_o, b_m]$ by

$$\hat{f}_i = \frac{\hat{F}_i}{W} = \frac{N_i}{N} \quad \frac{K}{b_m - a_o} \quad i=1, 2, 3 \ldots K \qquad \text{Probability Density}$$

and the probability distribution estimate defined at the class interval end points where i = 0, 1, 2, . . . , K+1.

$$\hat{F}(i) = \sum_{j=0}^{i} \hat{F}_j = W \sum_{j=0}^{i} \hat{p}_j$$

2.8 Ratio of Synchronous to Composite

The analysis of the ratio of synchronous to composite vibration levels measured in flight is documented for future reference. This data will be utilized in studies to relate flight to static firing data, the effect of vibration level amplitude on the ratio of synchronous to composite, evaluation of the FASCOS system and justification of vibration redlines.

The ratio of synchronous to composite vibration levels of Figures 33, 34, 35, and 36 for 100% and 104% power levels were calculated using the data stored in the MSFC Diagnostic Data Base. Both the composite (50-1000 Hz) and synchronous vibration levels in the data base are derived from a sliding 11 point average (0.4 second PSDs) which is equal to 4.4 seconds of data during each power level. The highest* or maximum value of this average is then stored in the data base** to represent the characteristic Grms vibration level at that power level. Since the Diagnostic Data Base Program does not record or track the time of occurrence during the flight the ratio may or may not represent the same time period of the flight. However, past history has shown the composite and synchronous track in a reasonable manner during most static firing tests and flights. This pseudo ratio shown in the figures should therefore be fairly representative of a ratio calculated from data recorded at the same time period. Additional investigations are planned to evaluate the skewed distribution on the high pressure fuel turbopump and the appearance of a bi-modal type of distribution on the high pressure oxidizer turbopump. One possibility is the ratio of synchronous to composite is a function of the vibration level. Also the investigation will include a comparison with the measured static ground test data.

---

*The vibration level stored in the Diagnostic Data Base and reported at data review meeting could be called the "highness" vibration level. Highness as defined in the Webster Dictionary "the highest of the nobility" with noble defined as "having excellent qualities; superior.". The MSFC Technical Monitor for this report has suggested contiguous average maximum vibration level as a descriptive term, while the Wyle Technical Reviewer has suggested noble vibration level. Only historical usage will finally define the terminology.

**The computer also skips random clipped signals and the output data is analyzed to purge the data base of invalid and extreme noisy data.

```
TESTS USED IN THIS ANALYSIS:

TEST #'S STS01,STS02,STS03,STS04,STS05,STS06,STS07,STS08,STS11,STS13,STS
41D,STS41G,STS51A,STS51B,STS51C,STS51D,STS51F,STS51G,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
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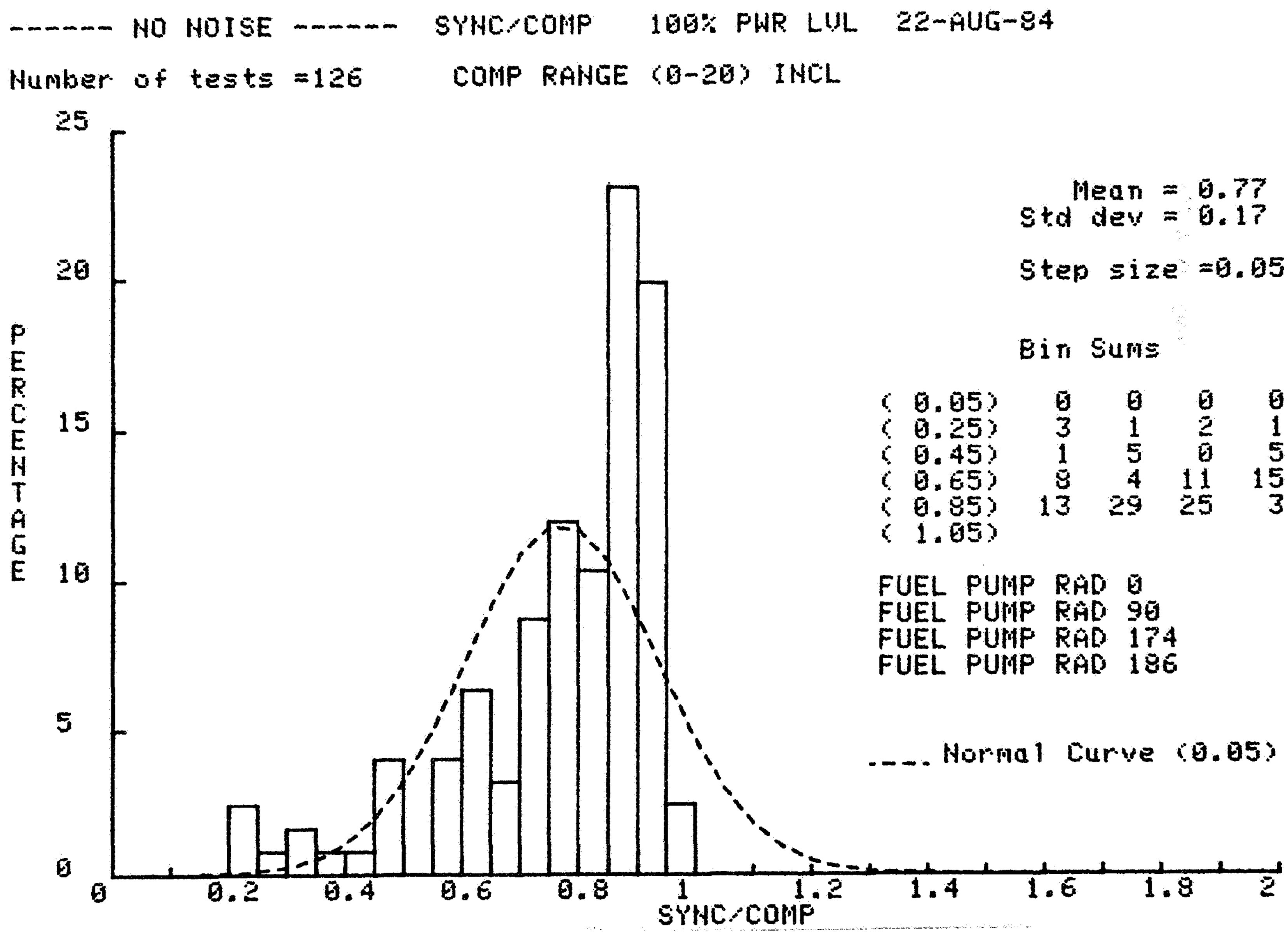

Figure 33. Probability Density of Synchronous/Composite Ratio for the HPFTP at 100% Power Level During Flight

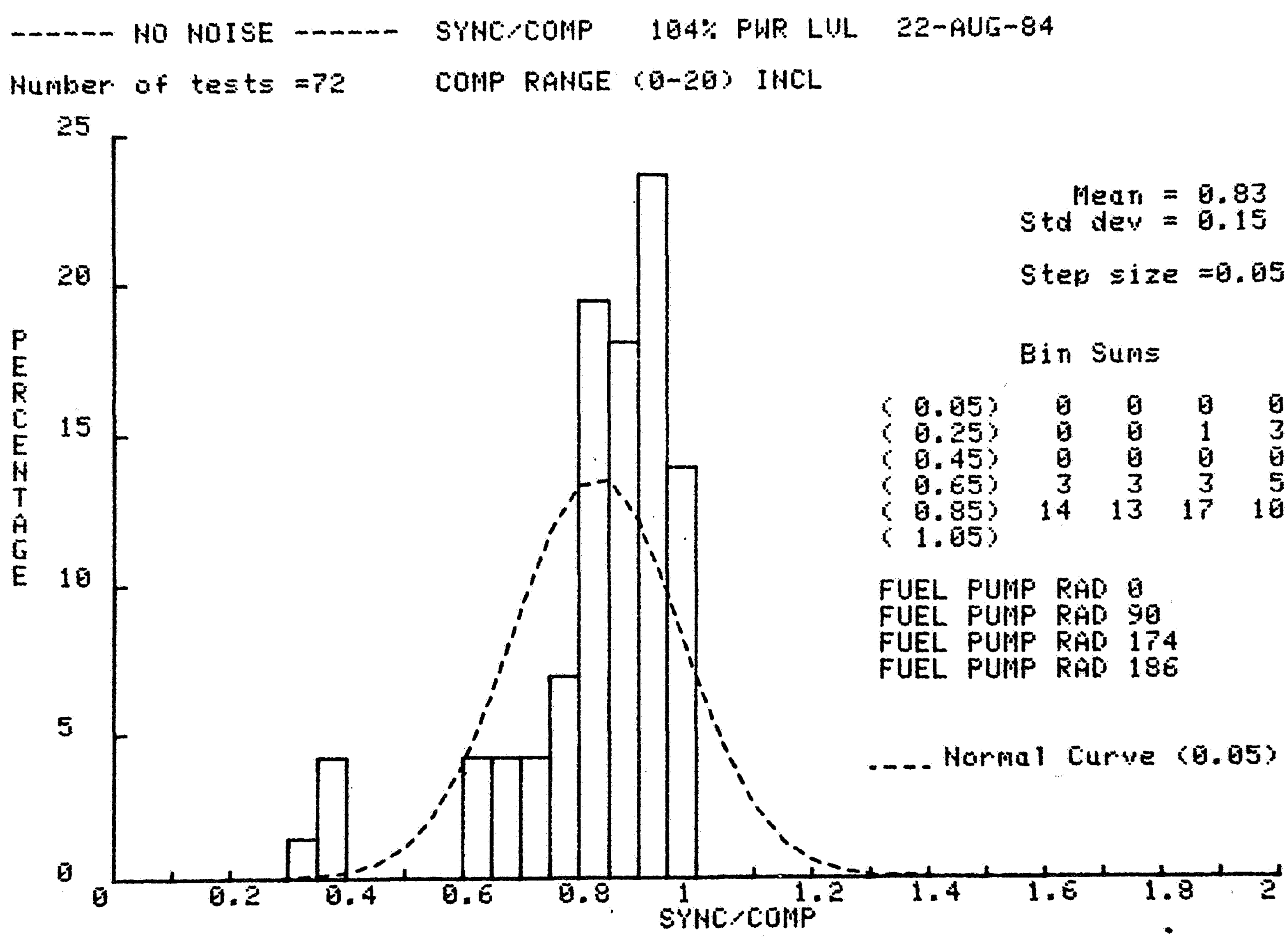

Figure 34. Probability Density of Synchronous/Composite Ratio for the HPFTP at 104% Power Level During Flight

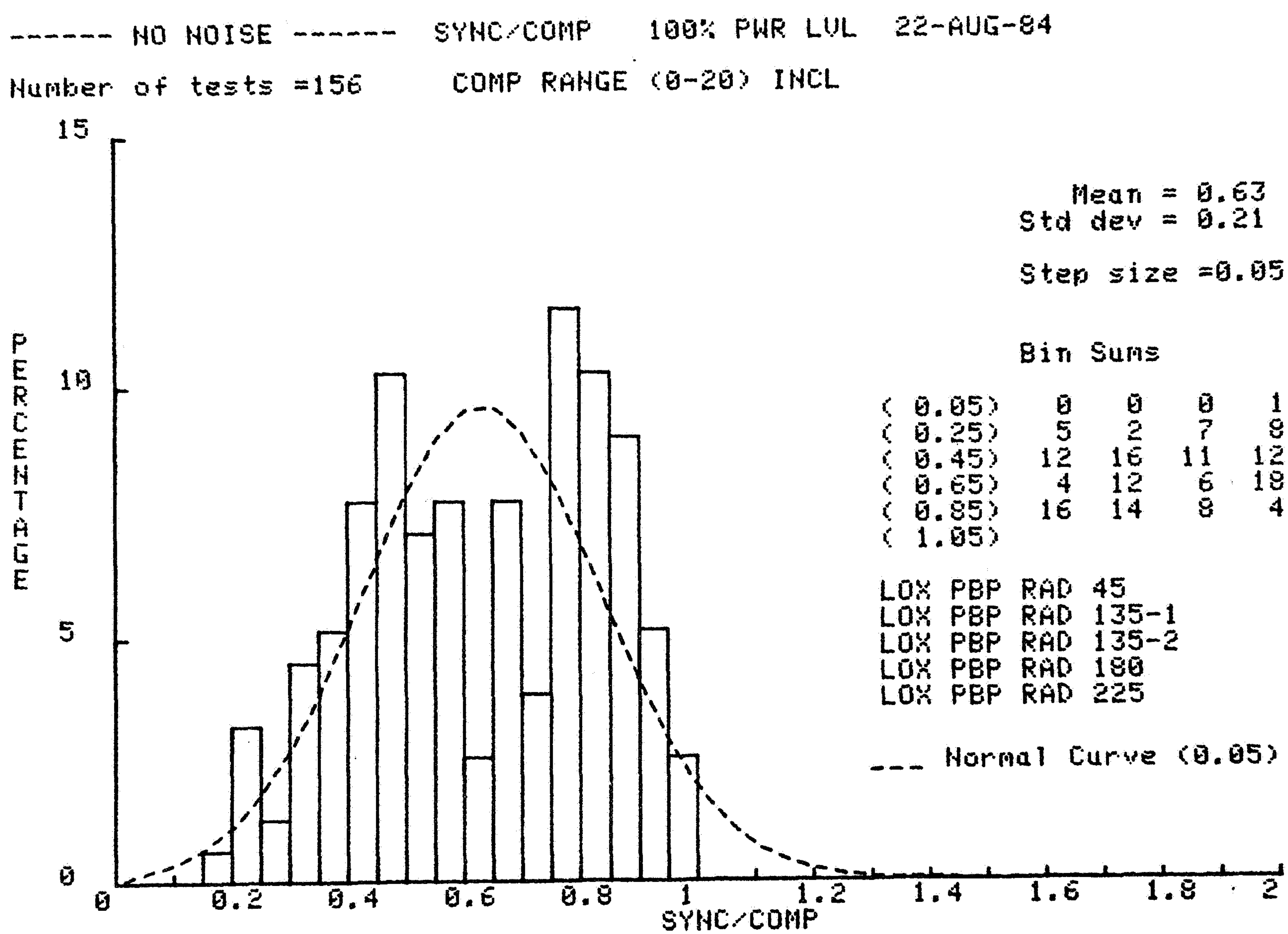

Figure 35. Probability Density of Synchronous/Composite Ratio for the HPOTP at 100% Power Level During Flight

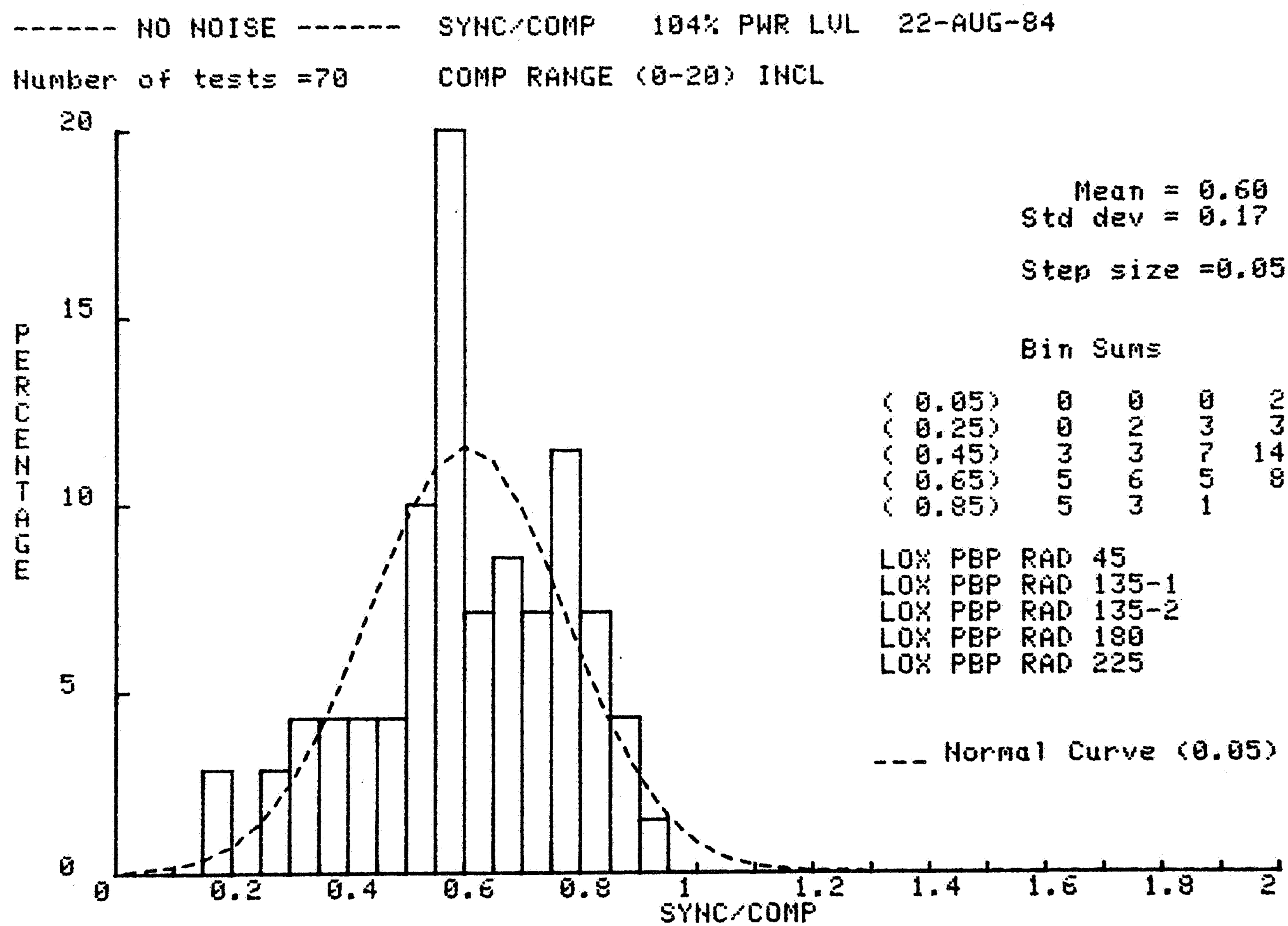

Figure 36. Probability Density of Synchronous/Composite Ratio for the HPOTP at 104% Power Level During Flight

2.9 Turbopump Rotational Speed History

The rotational speed of the high pressure oxidizer turbopump (HPOTP) and high pressure fuel turbopump (HPFTP) are shown in Figures 37 and 38. The speed is calculated from the synchronous frequency of the measured vibration data and represents the maximum speed of the pump during the flight at 100% and 104% power levels. The notation on the plot lists the flight number STS xx, engine position Ex and turbopump serial number.

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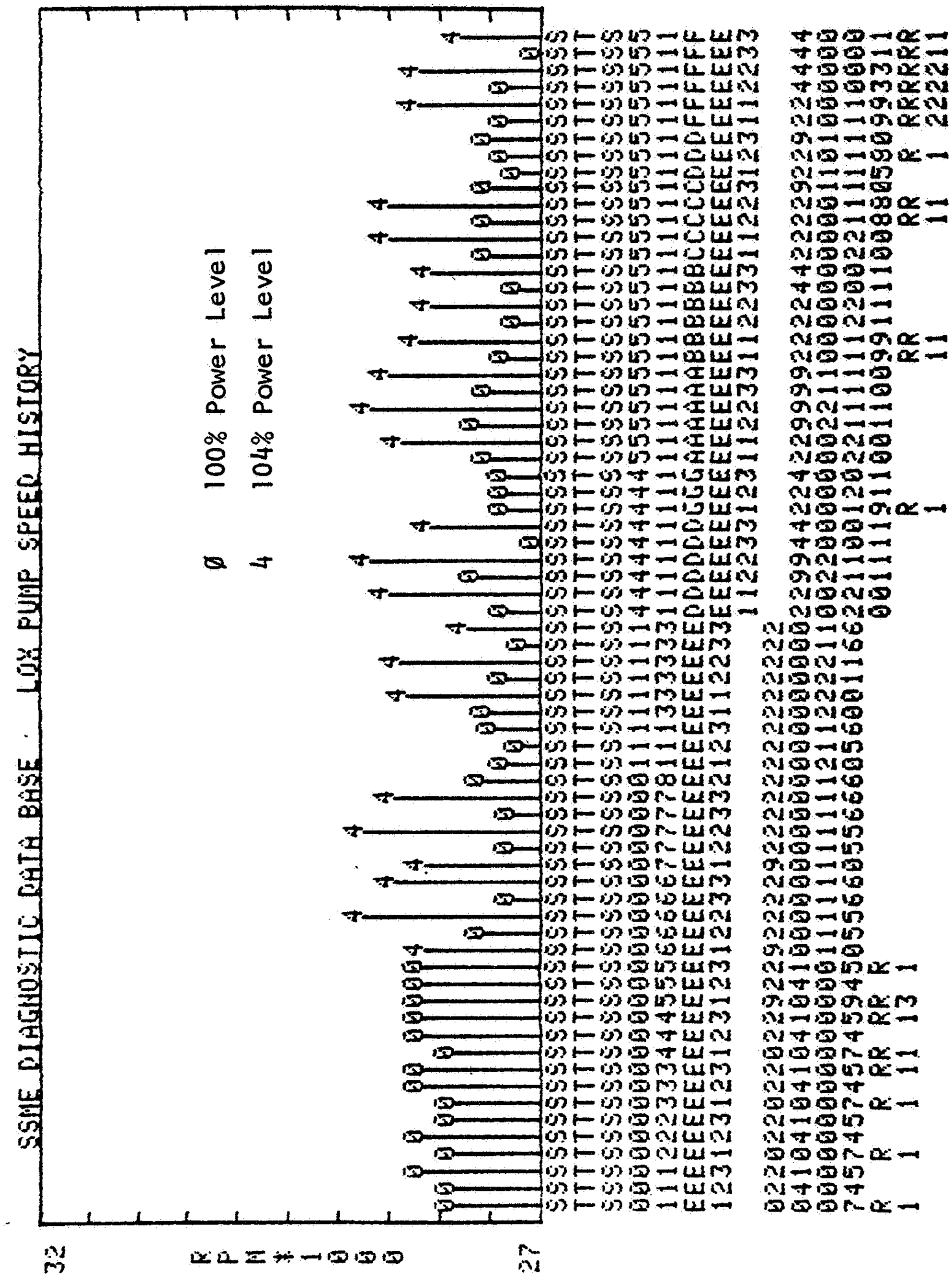

Figure 37. HPOTP Maximum Rotational Speed During Flight

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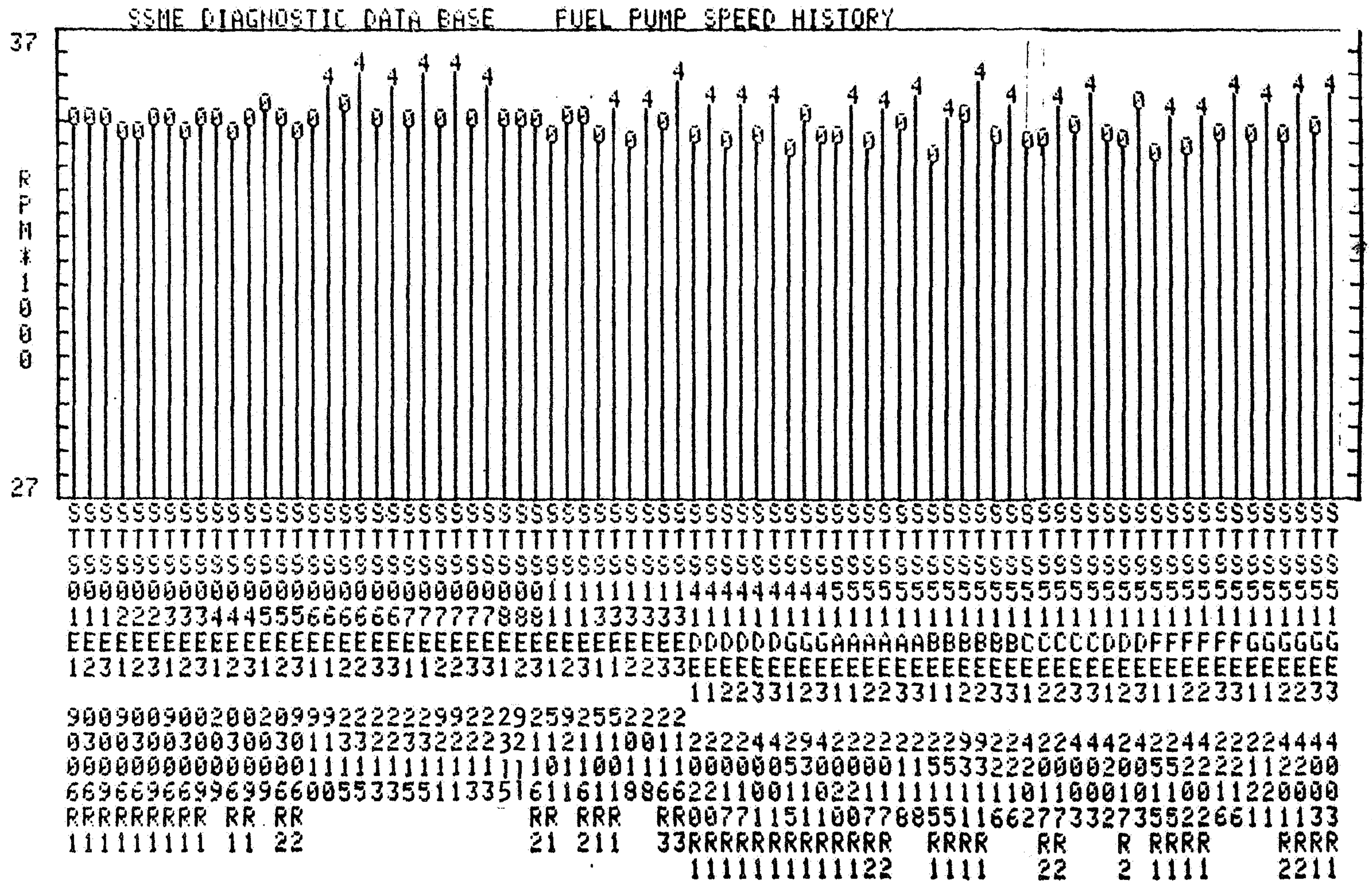

Figure 38. HPFTP Maximum Rotational Speed During Flight

3.0 REFERENCES

1. Lewallen, P., "SSME Vibration Data Base," (In publication MSFC/NASA TN), 1985.

2. Papoulis, A., "Probability Random Variables and Stochastic Processes," McGraw-Hill Book Company, NY, 1965, p. 148.

3. Hines, W. W. and D. C. Montgomery, "Probability and Statistics," Ronald Press Co., NY, 1972, p. 157.

4. Bendet, J. S. and A. G. Pierson, "Random Data: Analysis and Measurement Procedures," Wiley-Interscience, NY, 1971, p. 309.

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4.0 RESULTS

A summary of the mean vibration levels, the standard deviation, and maximum level measured on the SSME high pressure oxidizer and fuel turbopump during flight is shown in Figures 39 through 50.* The results are for the SSME operating at 104%, 100% and 65% power levels. Statistics are for each measurement location and the average of all locations which represents a spatial average around the turbopump. Both the composite (50-1000 Hz) and synchronous vibration levels were considered in this investigation.

Cumulative probability distribution plots are shown in Figures 51 through 62 with the classical Gamma distribution plotted as an overlay dashed line. These plots as discussed in Section 2.6 can provide a quick-look assessment of flight results as compared to this historical distribution of the previous flight data. The probability density for each power level for the oxidizer and fuel turbopumps is shown in Figures 63 through 74. These plots provide a quick assessment of the historical flight data scatter or dispersion from the mid-point or mean value whichever may be of interest. The tabulated data on each plot is the number of data points in each 0.5 Grms interval. Also the number of tests is equal to the number of test samples rather than the number of flights.

For future reference, flight numbers keyed into the computer are listed for the flights used in this analysis. The data sheets for each measurement are also included for reference.

* The data of STS Launch 27 (51-I) and 28 (51-J) are included in Appendix A. Both flights were nominal and will not have a significant effect on the statistical data of Figures 39 through 74.

```
TESTS USED IN THIS ANALYSIS:

TEST #'S STS01,STS02,STS03,STS04,STS05,STS06,STS07,STS08,STS11,STS13,STS
41D,STS41G,STS51A,STS51B,STS51C,STS51D,STS51F,STS51G,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

FLIGHT SUMMARY SHEETS

HPOTP AND HPFTP

104%, 100% AND 65% POWER LEVEL

Composite @104% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	3.0	1.0	5.0	3	1.9	1.0	3.0	18	3.4	1.5	7.3

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @104% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	3.0	1.0	5.2	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 104% Power Level

Grms	=	3.04
Standard Deviation	=	1.14
# Data Points	=	72

Figure 39. Summary of Composite Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

Synchronous @104% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	2.7	1.0	4.7	3	1.3	1.0	2.3	18	2.6	0.8	3.8

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @104% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	2.5	1.0	5.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Synchronous 104% Power Level

Grms	=	2.53
Standard Deviation	=	0.99
# Data Points	=	72

Figure 40. Summary of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

Composite @104X Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	2.6	0.9	4.7	24	2.8	0.8	4.7	19	2.9	0.5	3.8

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @104X Power Level

Test Stand	LOX PBP RAD 180 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 225 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX TURB RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	0	0.0	0.0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 104% Power Level

Grms	=	2.76
Standard Deviation	=	0.75
# Data Points	=	70

Figure 41. Summary of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

Synchronous @104% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	1.5	0.7	3.9	24	1.9	0.8	3.4	20	1.8	0.7	2.7

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @104% Power Level

Test Stand	LOX PBP RAD 180 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 225 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX TURB RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	0	0.0	0.0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Synchronous 104% Power Level

Grms	=	1.69
Standard Deviation	=	0.76
# Data Points	=	71

Figure 42. Summary of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

Composite @100% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	36	2.3	1.0	5.3	13	3.6	1.2	5.0	23	2.5	1.5	7.2

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @100% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	54	2.7	1.5	7.2	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 100% Power Level

Grms	=	2.66
Standard Deviation	=	1.36
# Data Points	=	126

Figure 43. Summary of Composite Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

Synchronous @100% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	36	2.0	1.0	5.2	13	2.6	1.2	4.5	23	1.7	0.7	3.4

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @100% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	54	2.2	1.4	6.4	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Synchronous 100% Power Level

Grms	=	2.08
Standard Deviation	=	1.20
# Data Points	=	126

Figure 44. Summary of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

Composite @100% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	54	2.7	1.1	7.0	50	2.8	1.2	6.5	38	3.2	1.3	6.5

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @100% Power Level

Test Stand	LOX PBP RAD 180 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 225 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX TURB RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	15	3.4	0.8	5.5	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 100% Power Level

Grms	=	2.93
Standard Deviation	=	1.17
# Data Points	=	157

Figure 45. Summary of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

Synchronous @100% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	54	1.6	1.1	6.0	50	2.1	1.3	5.9	39	2.2	1.2	5.3

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @100% Power Level

Test Stand	LOX PBP RAD 180 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 225 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX TURB RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	14	2.1	0.9	4.1	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average	Synchronous	100% Power Level
Grms	=	1.93
Standard Deviation	=	1.21
# Data Points	=	157

Figure 46. Summary of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

Composite @ 65% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	1.1	0.3	1.9	2	1.0	0.2	1.1	24	1.3	0.5	2.9

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @ 65% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	26	1.2	0.3	2.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 100% Power Level

Grms	=	1.17
Standard Deviation	=	0.38
# Data Points	=	76

Figure 47. Summary of Composite Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

Synchronous @ 65% Power Level

Test Stand	FUEL PUMP RAD 0 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL PUMP RAD 174 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	24	0.7	0.3	1.1	2	0.5	0.1	0.5	24	0.7	0.3	1.3

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @ 65% Power Level

Test Stand	FUEL PUMP RAD 186 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB RAD 90 # Tests	$\bar{G}$ rms	Sig	Max G rms	FUEL TURB AXIAL # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	26	0.8	0.3	1.3	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Synchronous 65% Power Level

Grms	=	0.71
Standard Deviation	=	0.30
# Data Points	=	76

Figure 48. Summary of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

Composite @ 65% Power Level

	LOX PBP RAD 45				LOX PBP RAD 135-1				LOX PBP RAD 135-2			
Test Stand	# Tests	$\bar{G}$ rms	Sig	Max G rms	# Tests	$\bar{G}$ rms	Sig	Max G rms	# Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	1.0	0.2	1.4	24	0.9	0.1	1.1	24	0.9	0.1	1.1

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Composite @ 65% Power Level

	LOX PBP RAD 180				LOX PBP RAD 225				LOX TURB RAD 45			
Test Stand	# Tests	$\bar{G}$ rms	Sig	Max G rms	# Tests	$\bar{G}$ rms	Sig	Max G rms	# Tests	$\bar{G}$ rms	Sig	Max G rms
STS	0	0.0	0.0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Composite 65% Power Level

Grms	=	0.92
Standard Deviation	=	0.18
# Data Points	=	75

Figure 49. Summary of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

Synchronous @ 65% Power Level

Test Stand	LOX PBP RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-1 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 135-2 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	27	0.4	0.3	0.9	24	0.4	0.2	0.8	25	0.3	0.2	0.8

STATISTICAL SUMMARY OF SSME VIBRATION DATA 23-AUG-85

Synchronous @ 65% Power Level

Test Stand	LOX PBP RAD 180 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX PBP RAD 225 # Tests	$\bar{G}$ rms	Sig	Max G rms	LOX TURB RAD 45 # Tests	$\bar{G}$ rms	Sig	Max G rms
STS	0	0.0	0.0	0.0	0	0.0	0.0	0.0	0	0.0	0.0	0.0

Spatial Average Synchronous 65% Power Level

Grms	=	0.38
Standard Deviation	=	0.22
# Data Points	=	76

Figure 50. Summary of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

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FLIGHT CUMULATIVE PROBABILITY DISTRIBUTIONS

HPOTP AND HPFTP

104%, 100% AND 65% POWER LEVEL

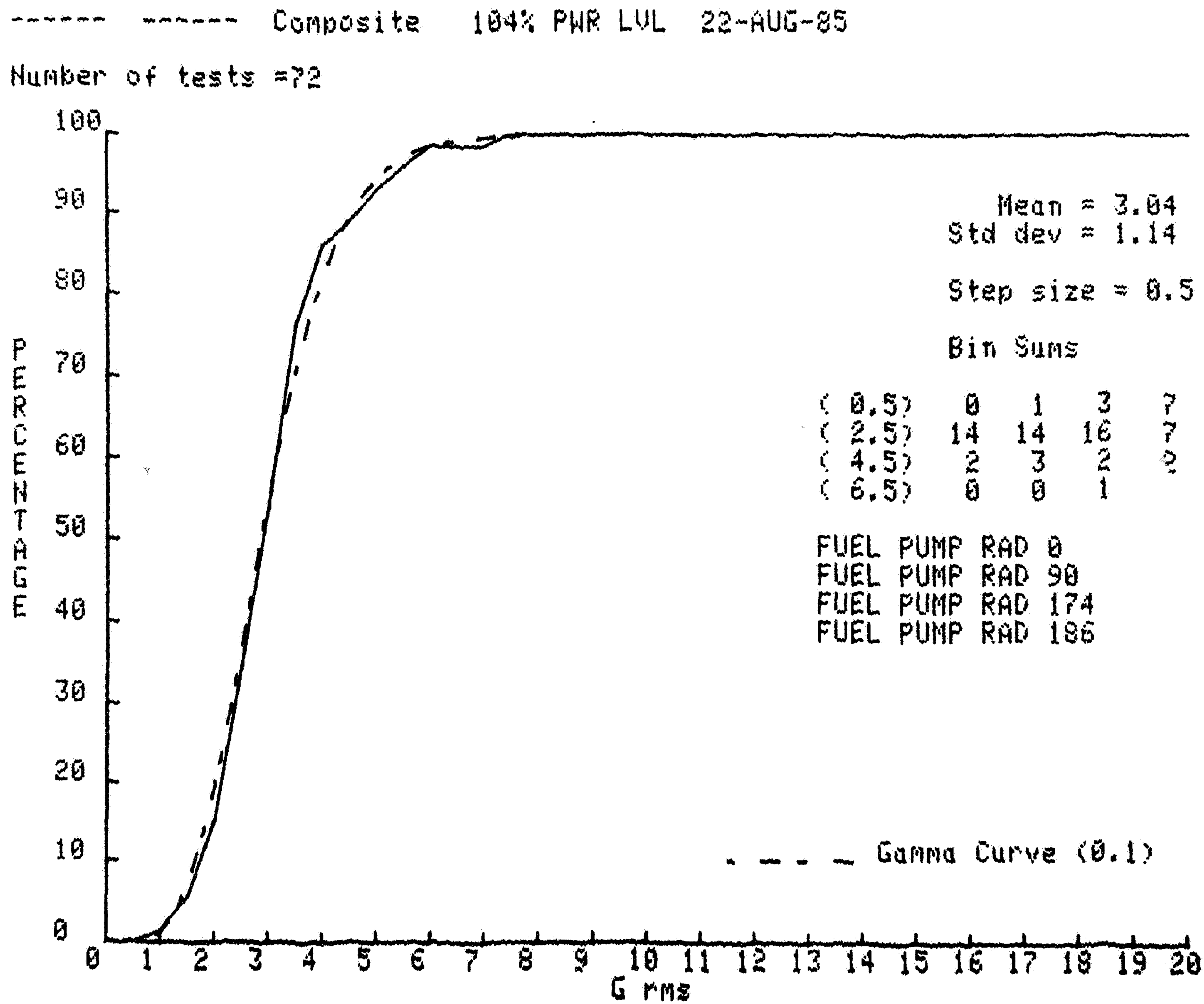

Figure 51. Cumulative Distribution of Composite Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

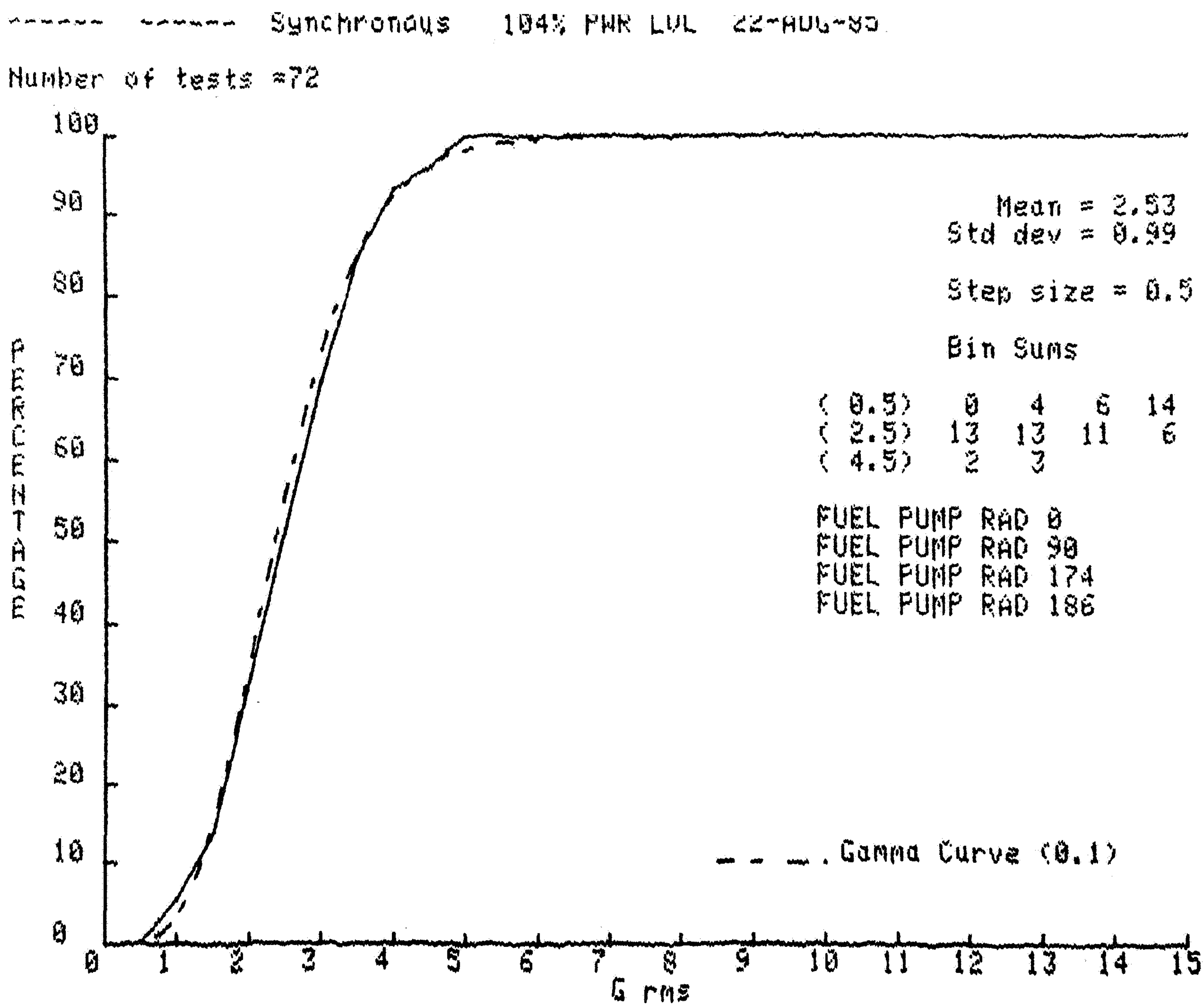

Figure 52. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

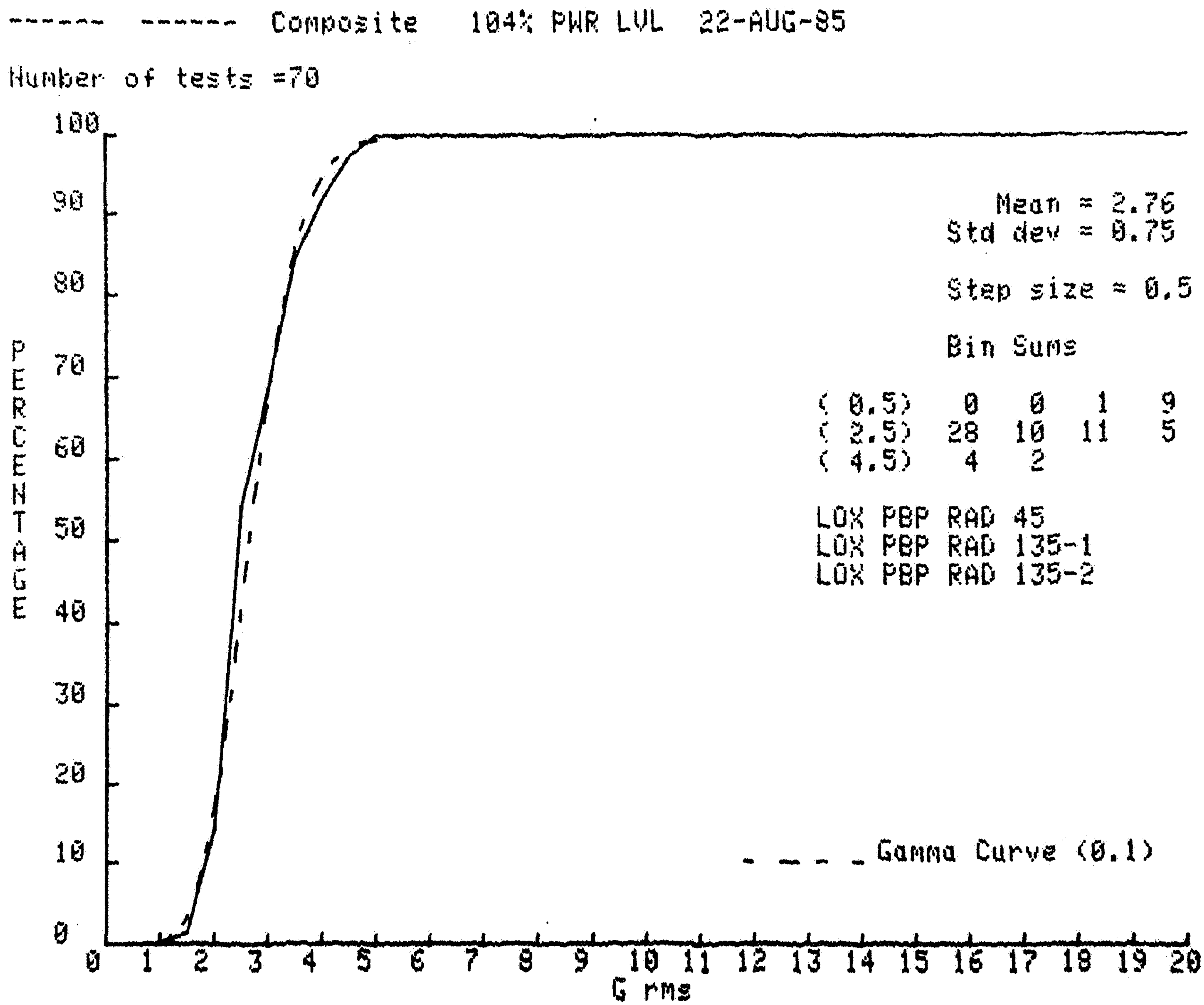

Figure 53. Cumulative Distribution of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

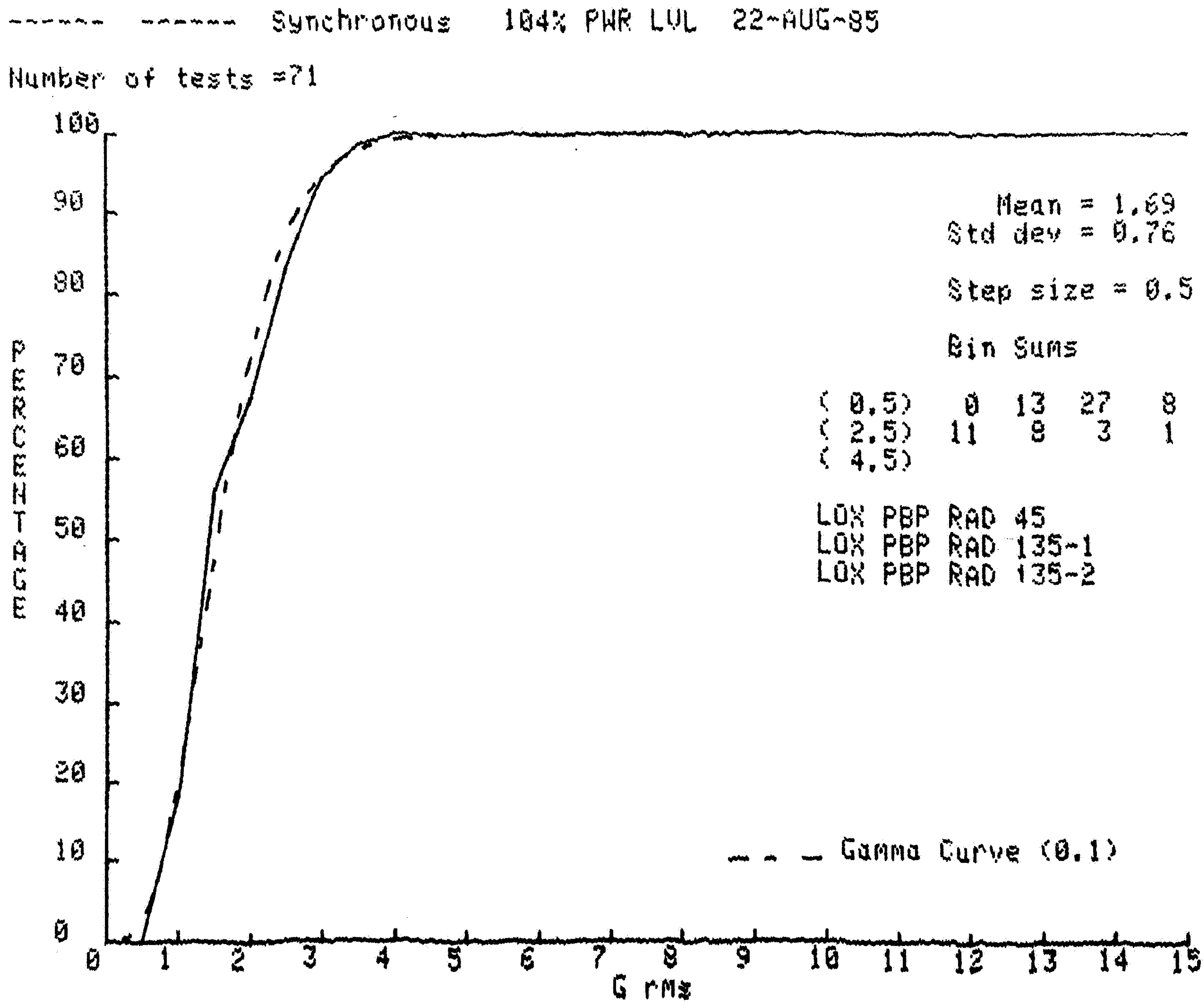

Figure 54. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

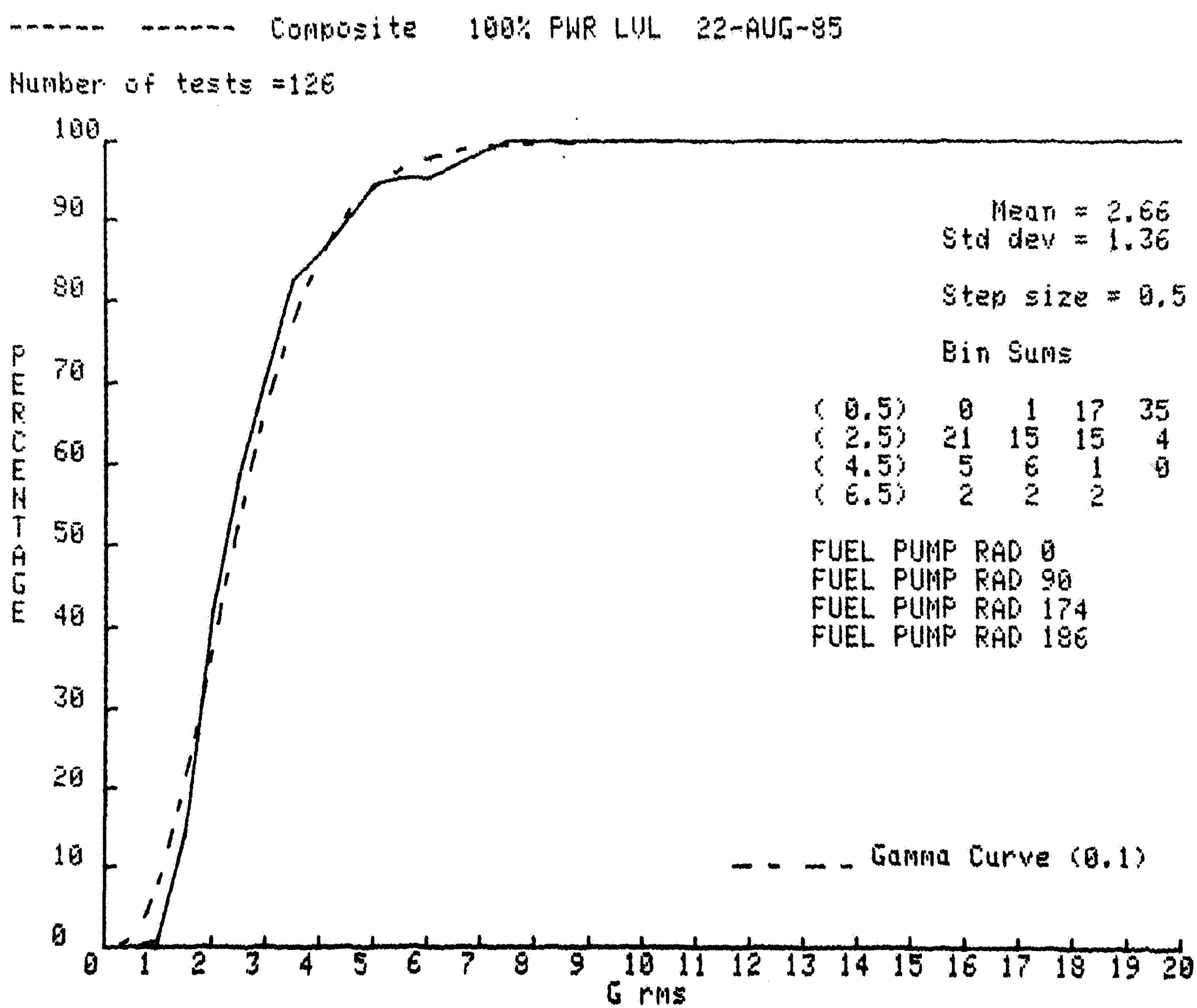

Figure 55. Cumulative Distribution of Composite Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

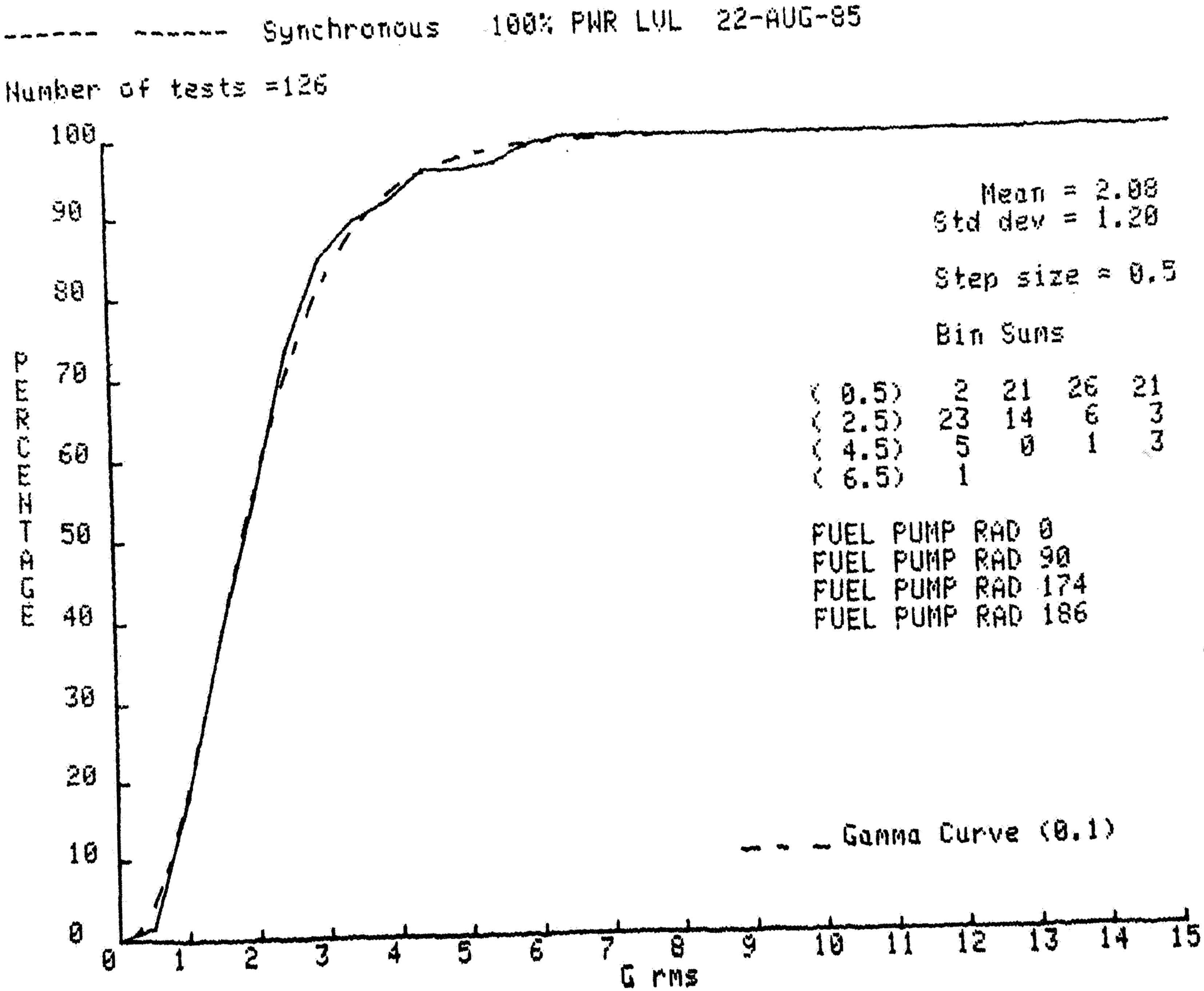

Figure 56. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

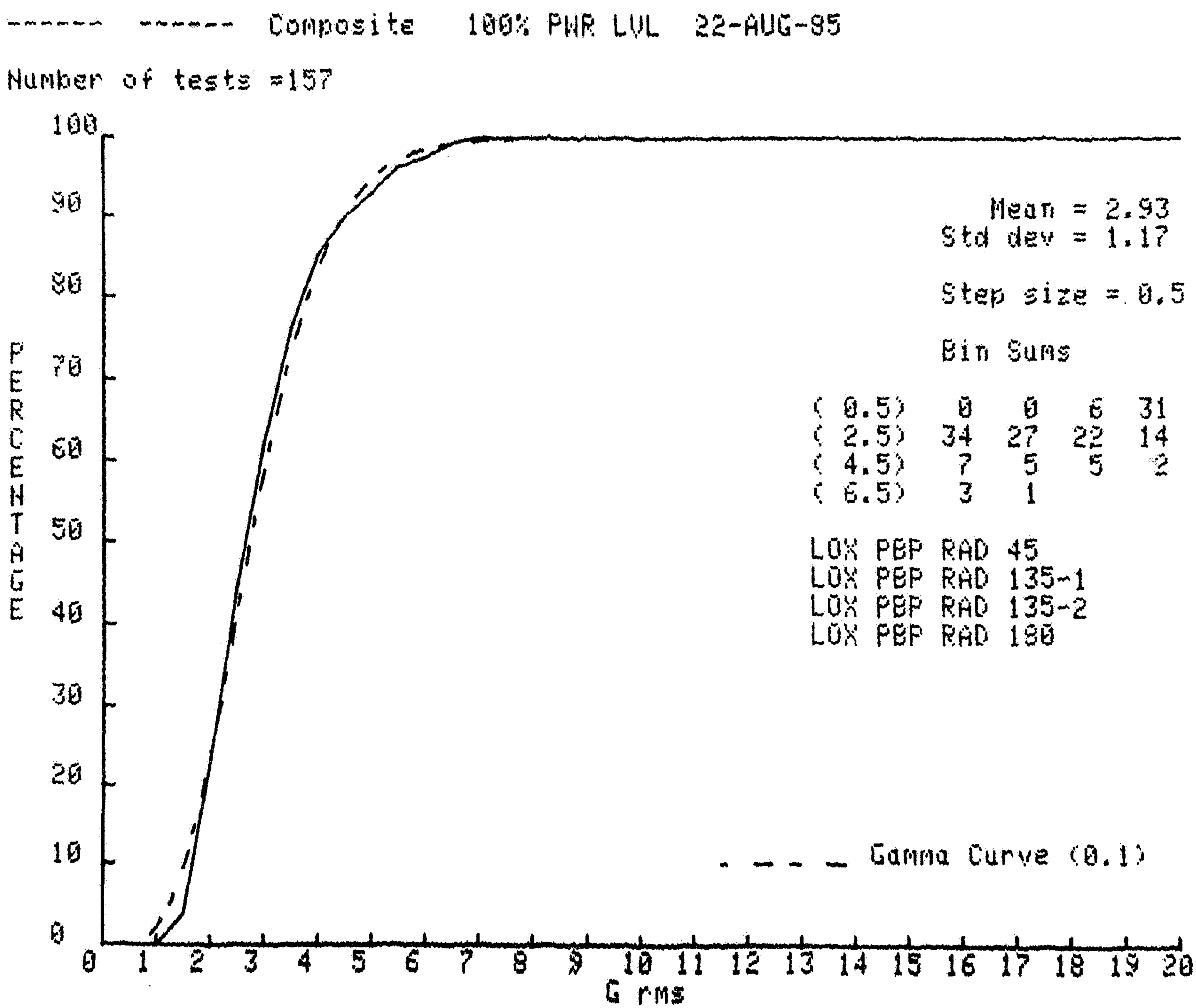

Figure 57. Cumulative Distribution of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

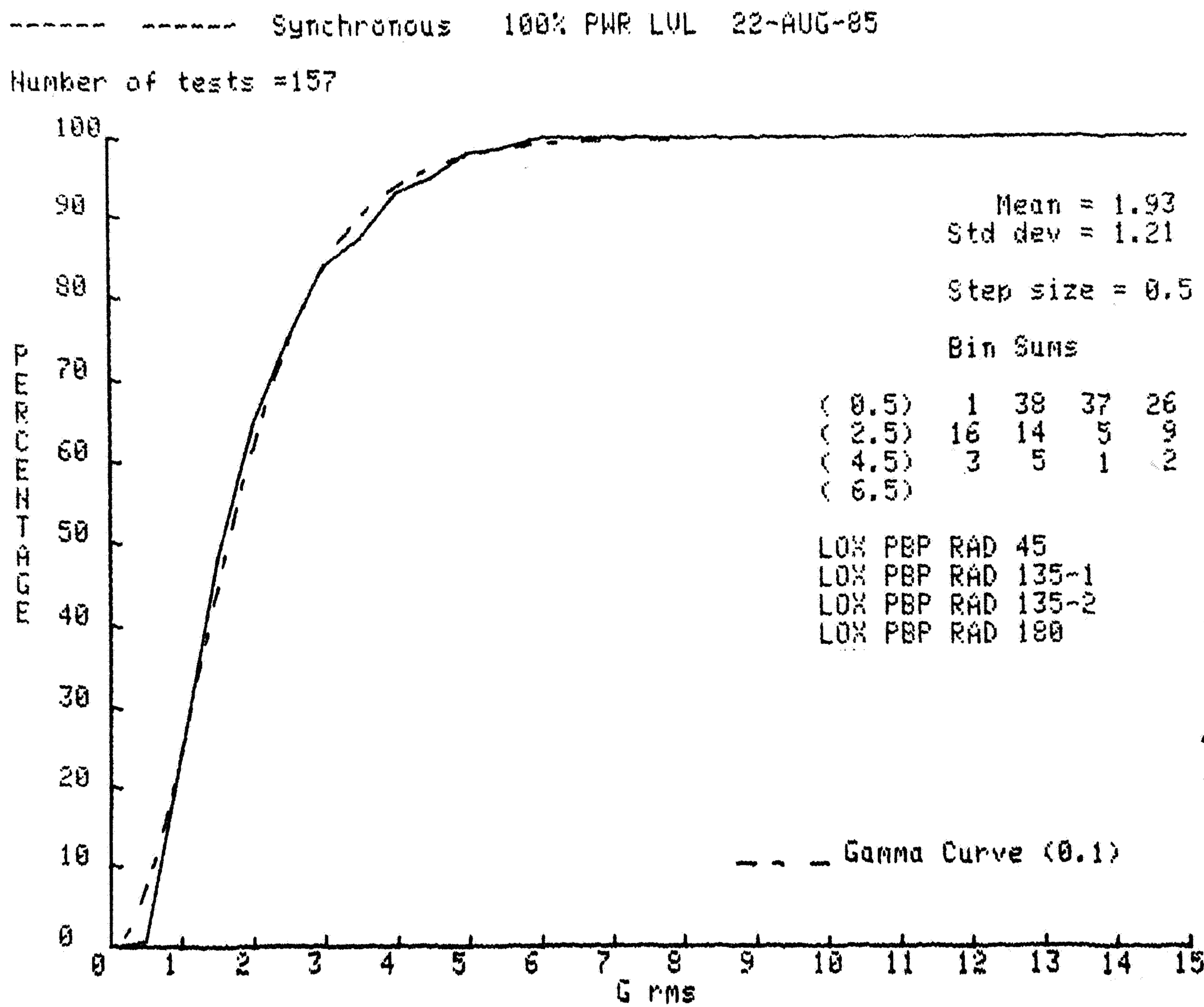

Figure 58. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

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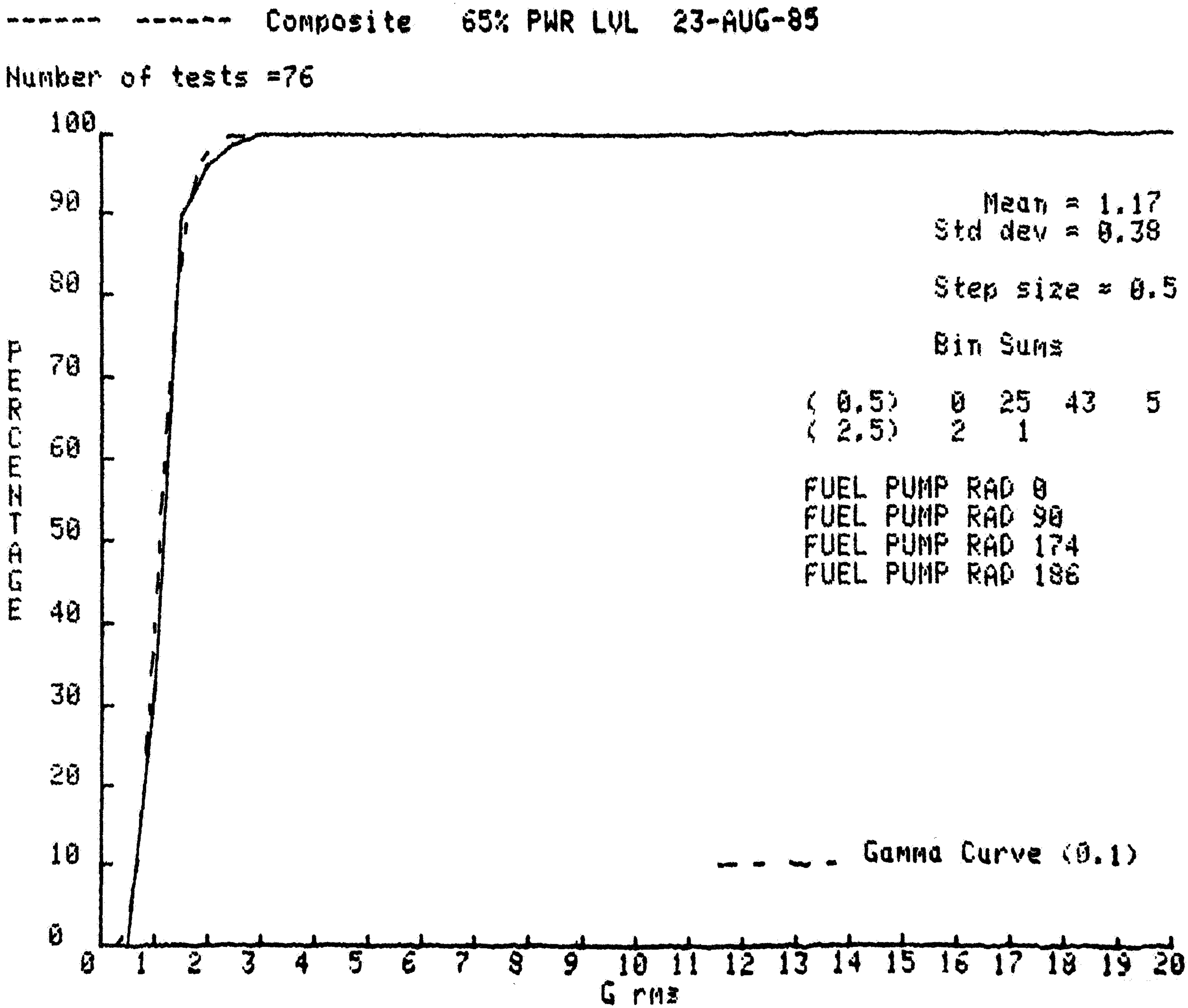

Figure 59. Cumulative Distribution of Composite Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

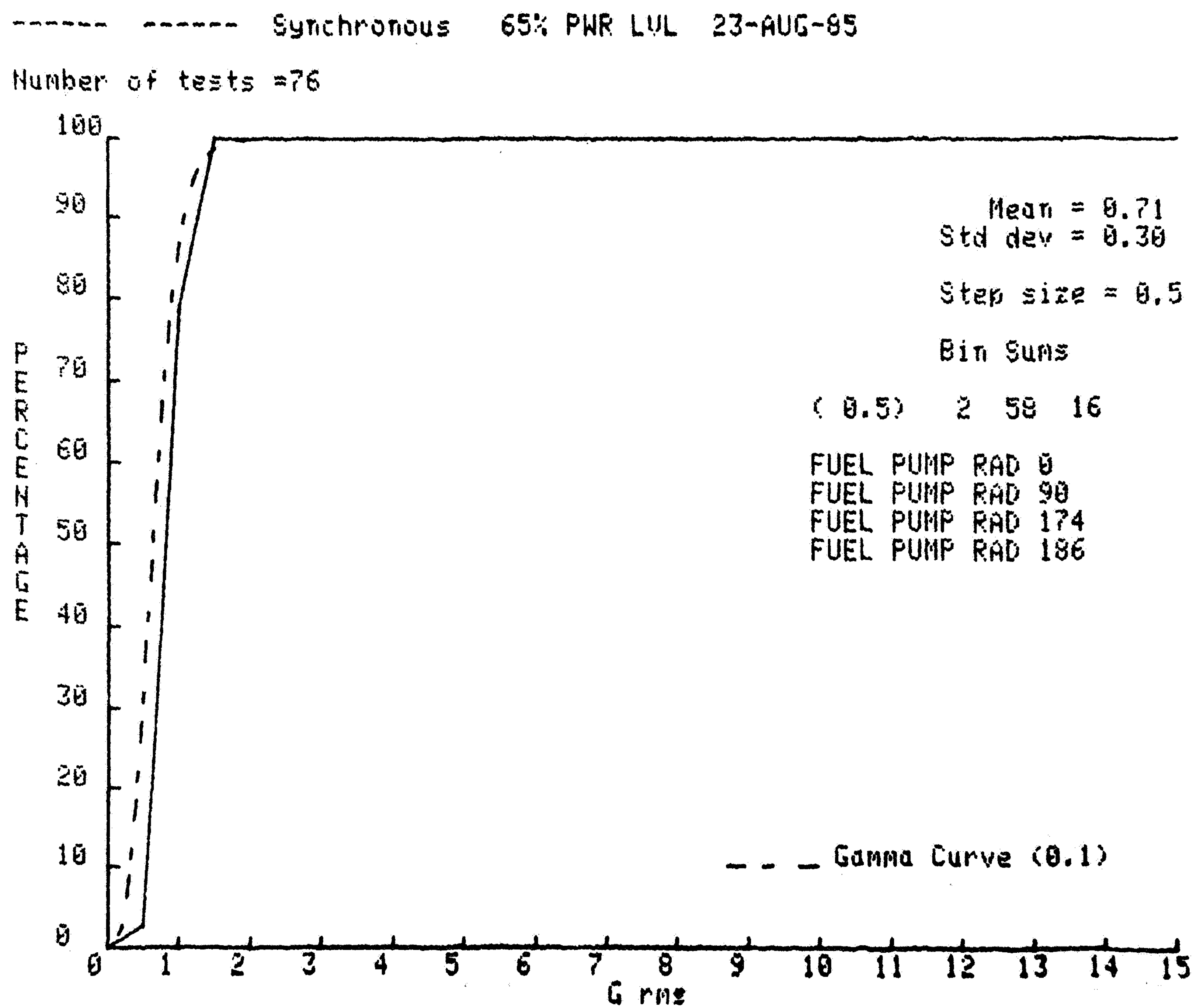

Figure 60. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

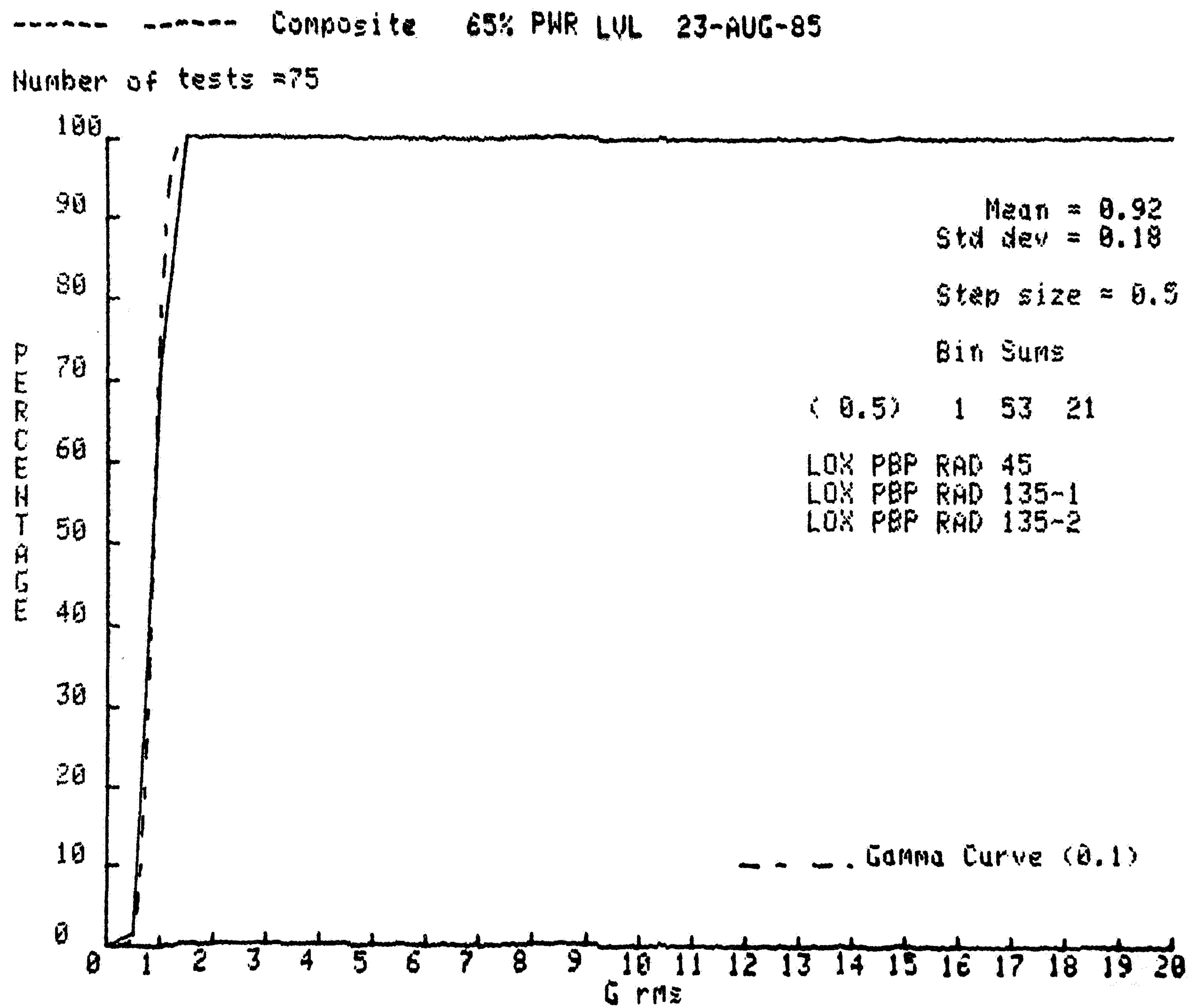

Figure 61. Cumulative Distribution of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

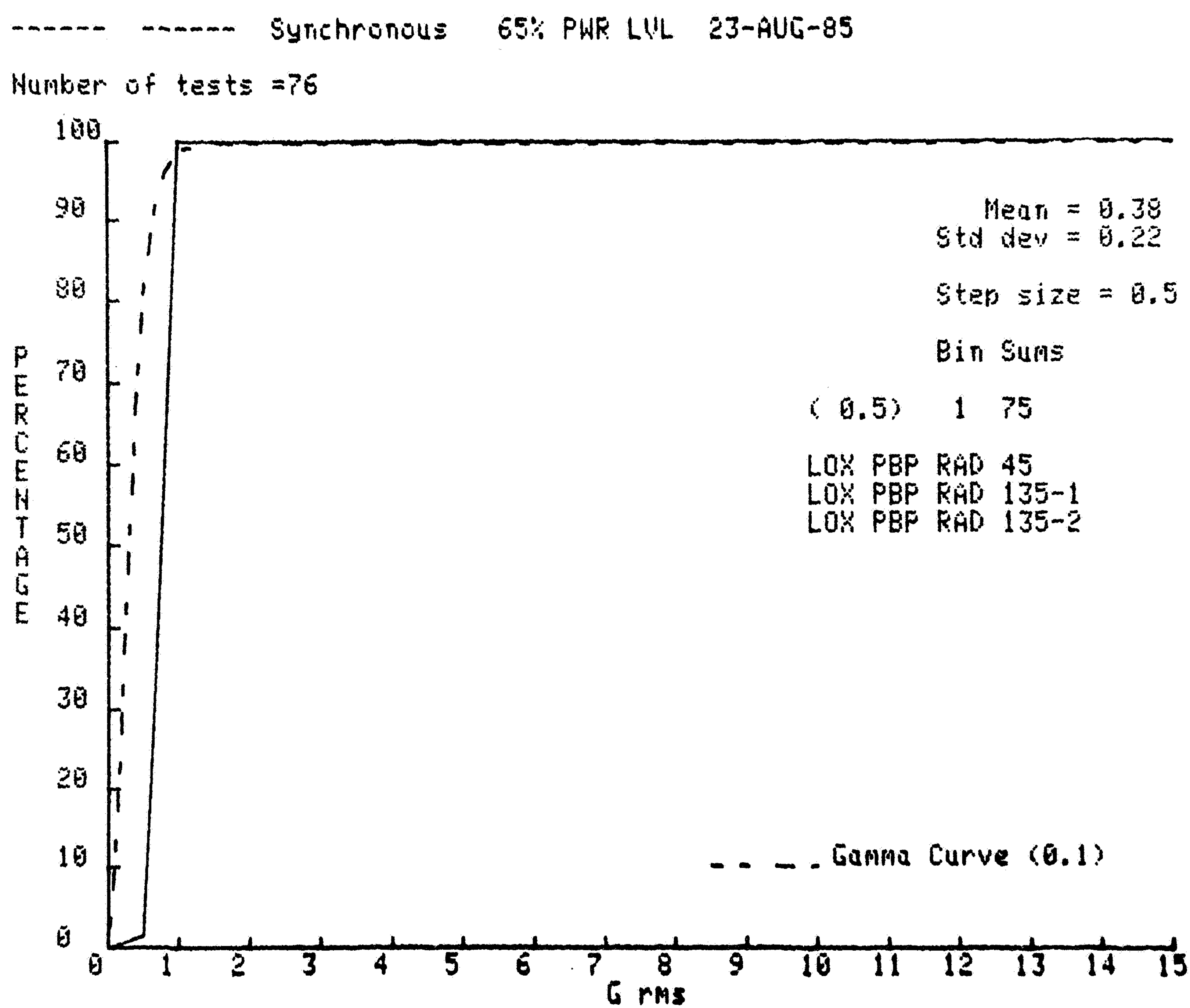

Figure 62. Cumulative Distribution of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

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FLIGHT PROBABILITY DENSITY FUNCTION

HPOTP AND HPFTP

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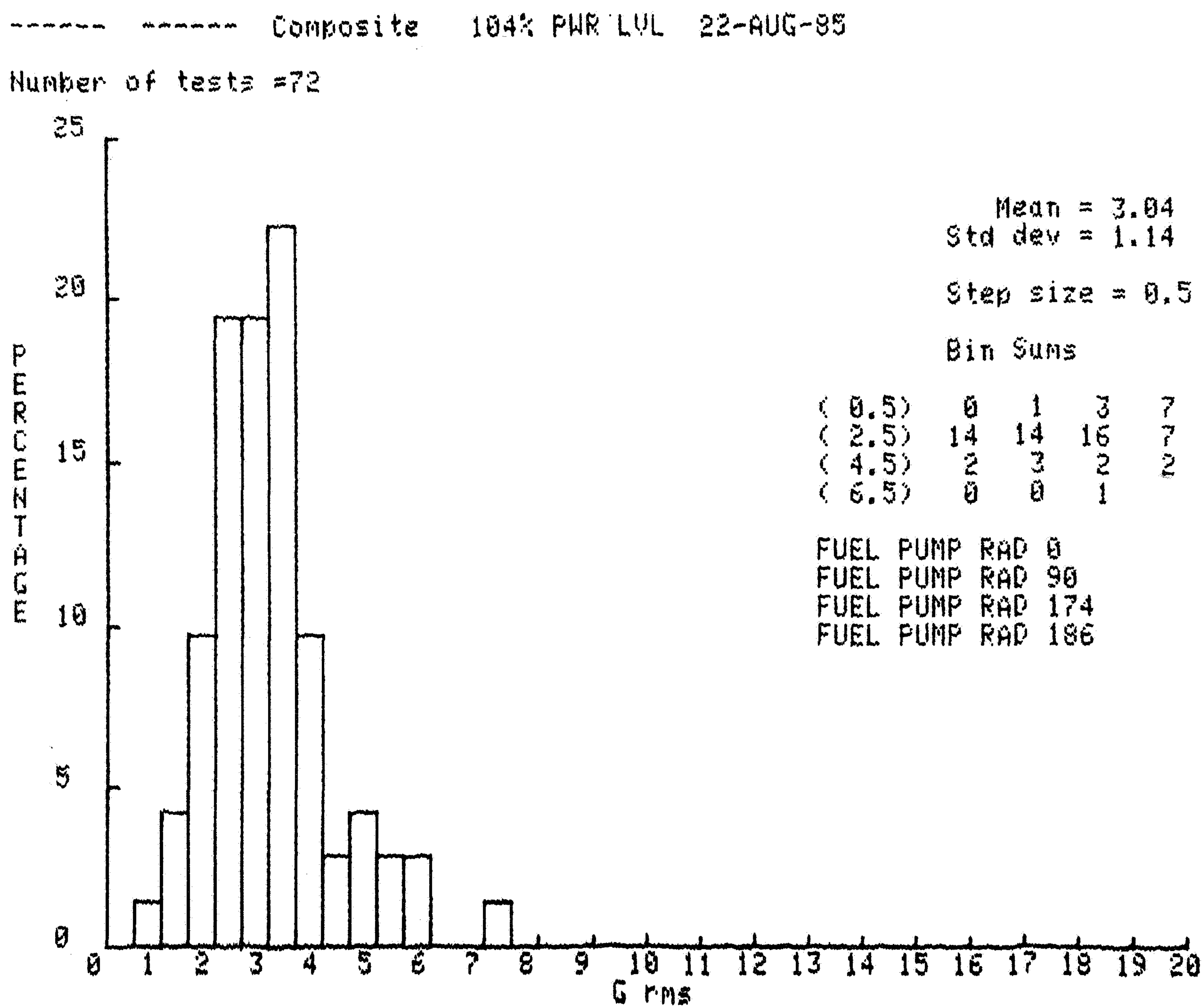

Figure 63. Probability Density of Composite Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

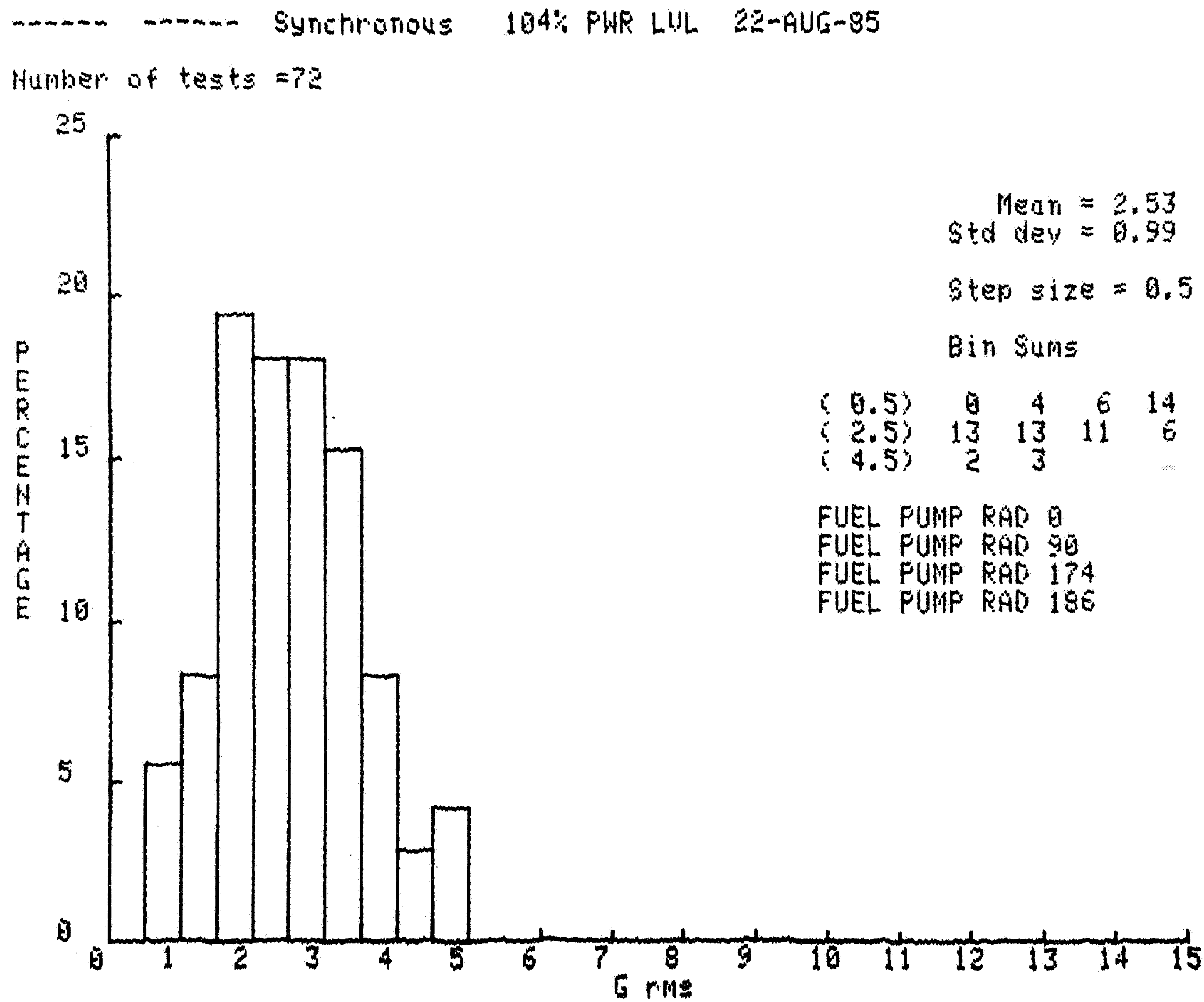

Figure 64. Probability Density of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 104% Power Level During Flight

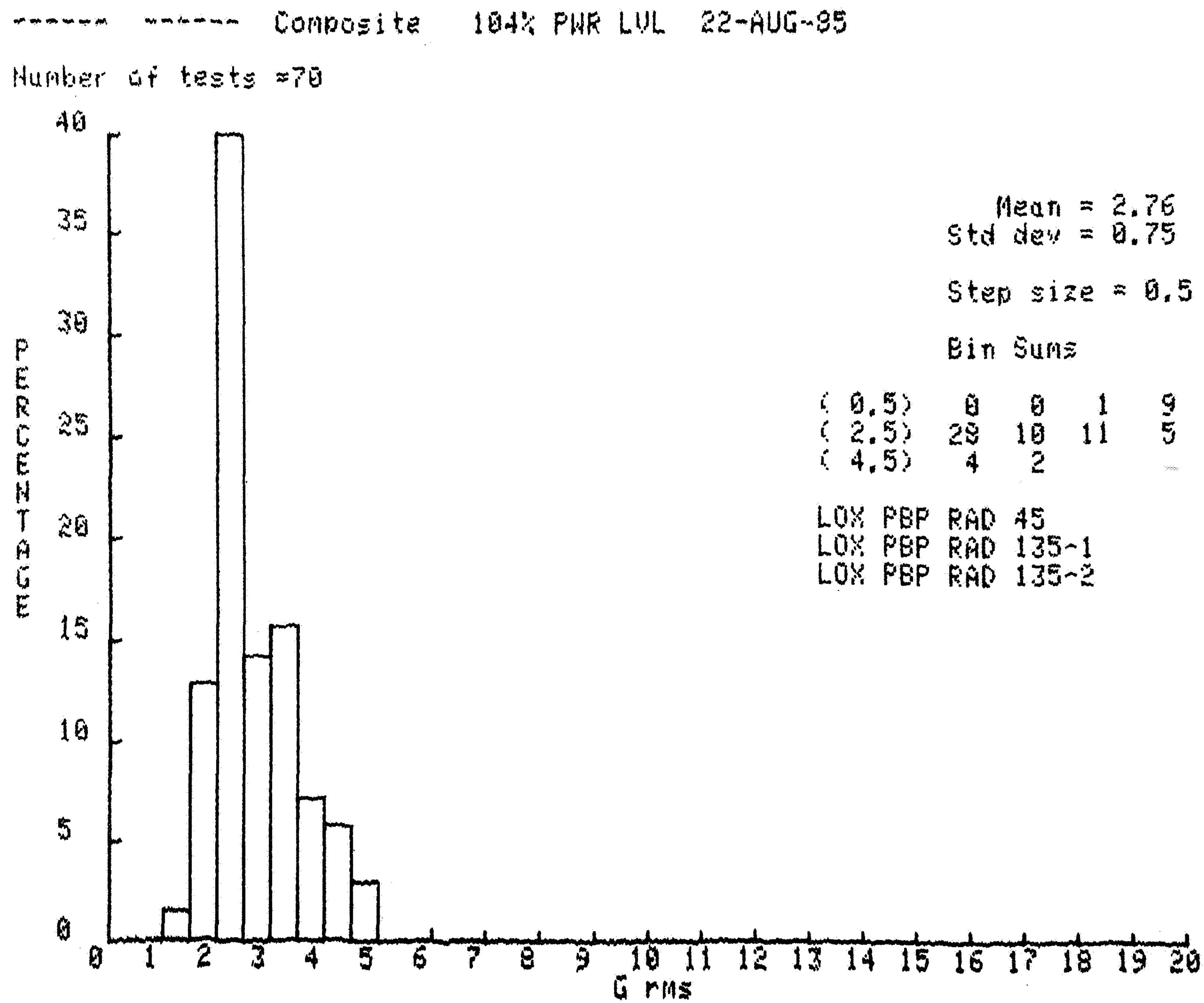

Figure 65. Probability Density of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

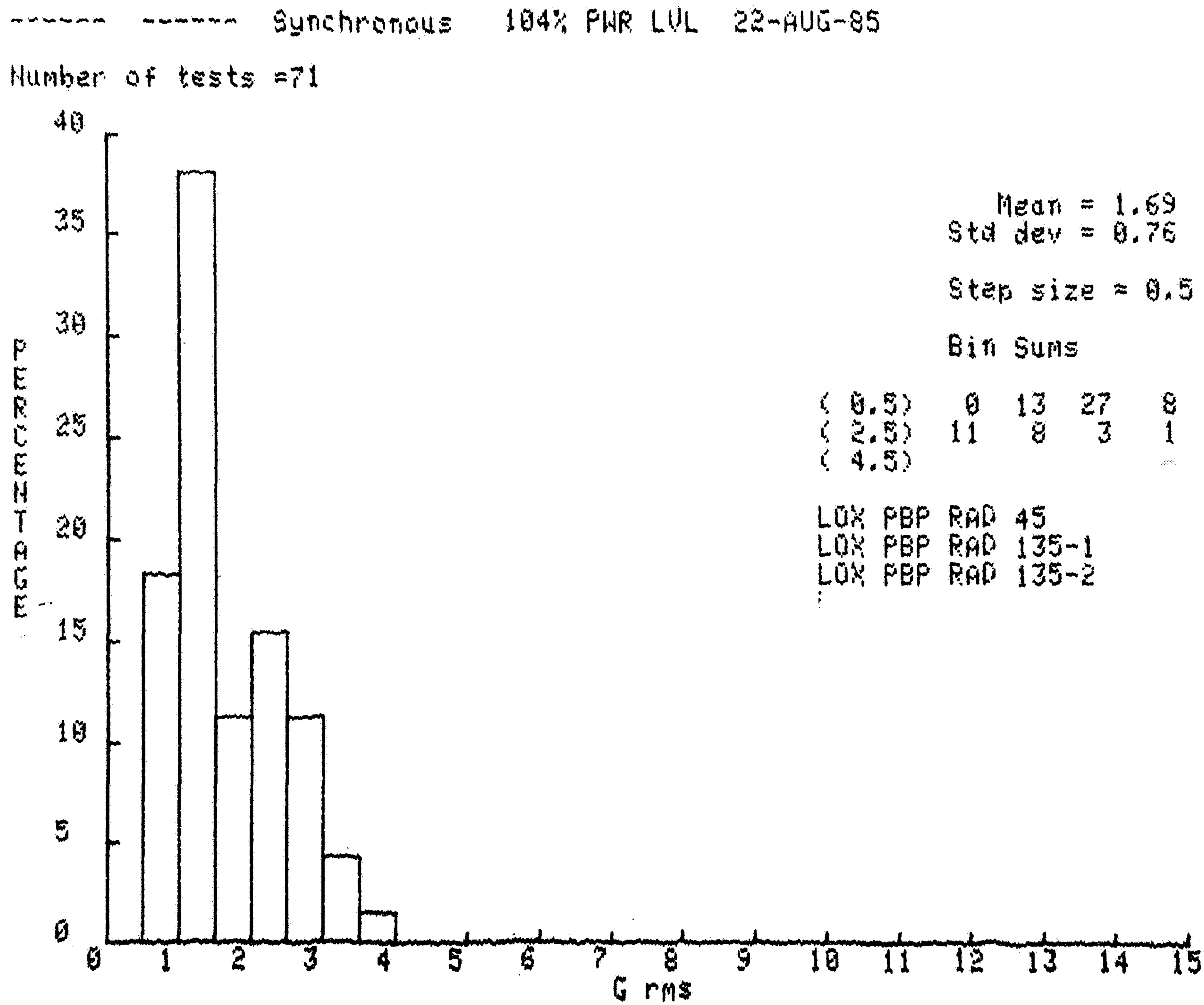

Figure 66. Probability Density of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 104% Power Level During Flight

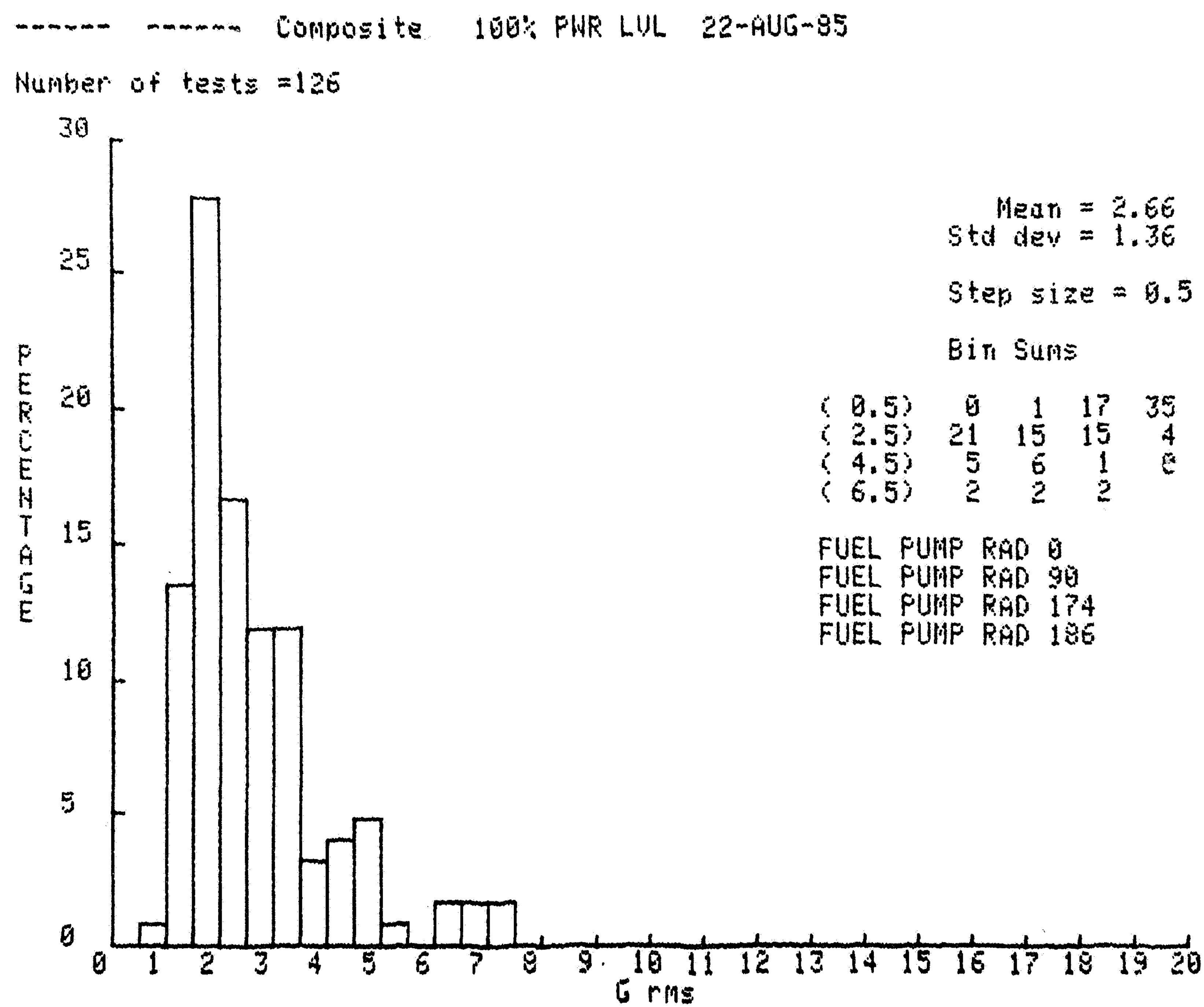

Figure 67. Probability Density of Composite Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

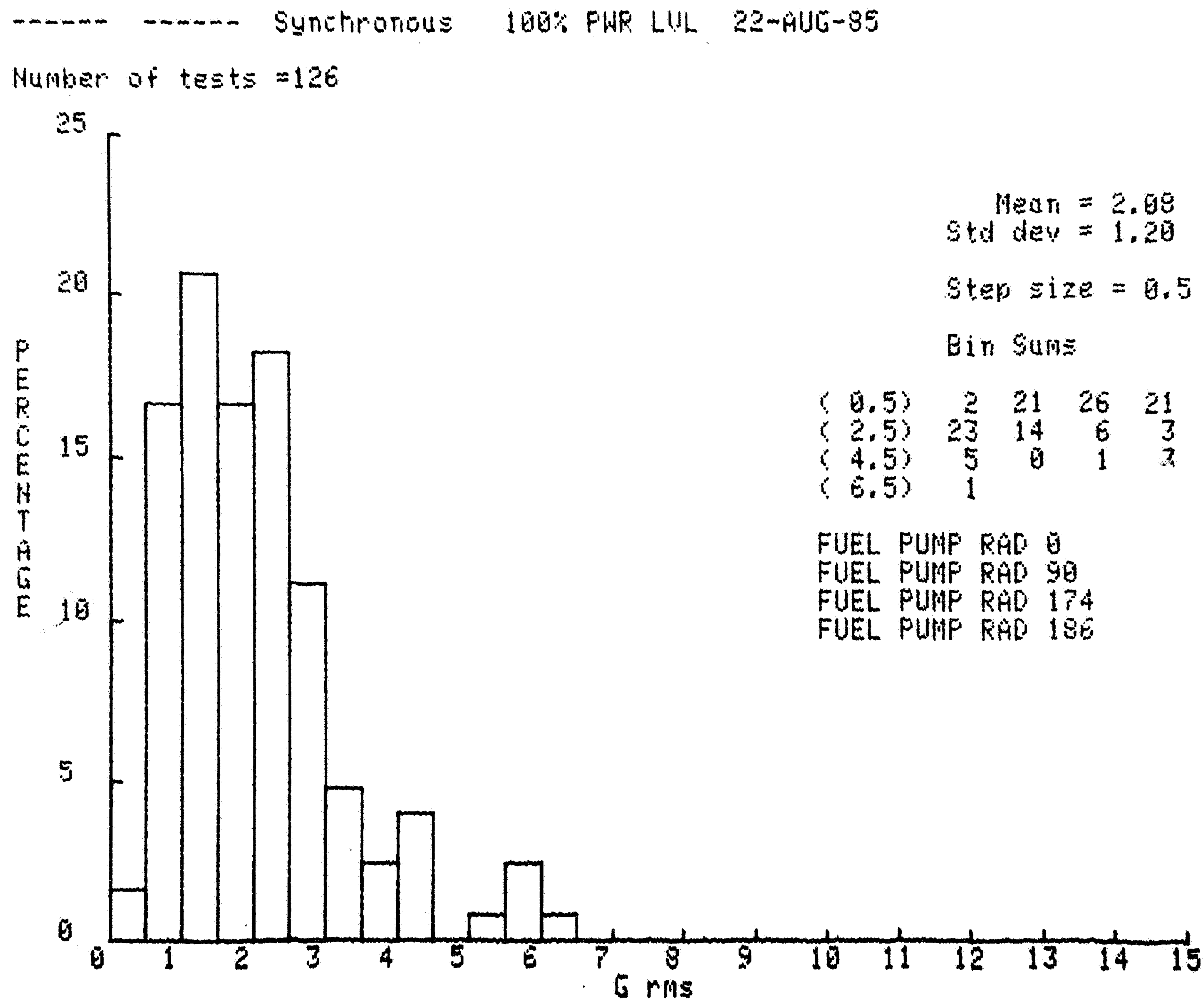

Figure 68. Probability Density of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 100% Power Level During Flight

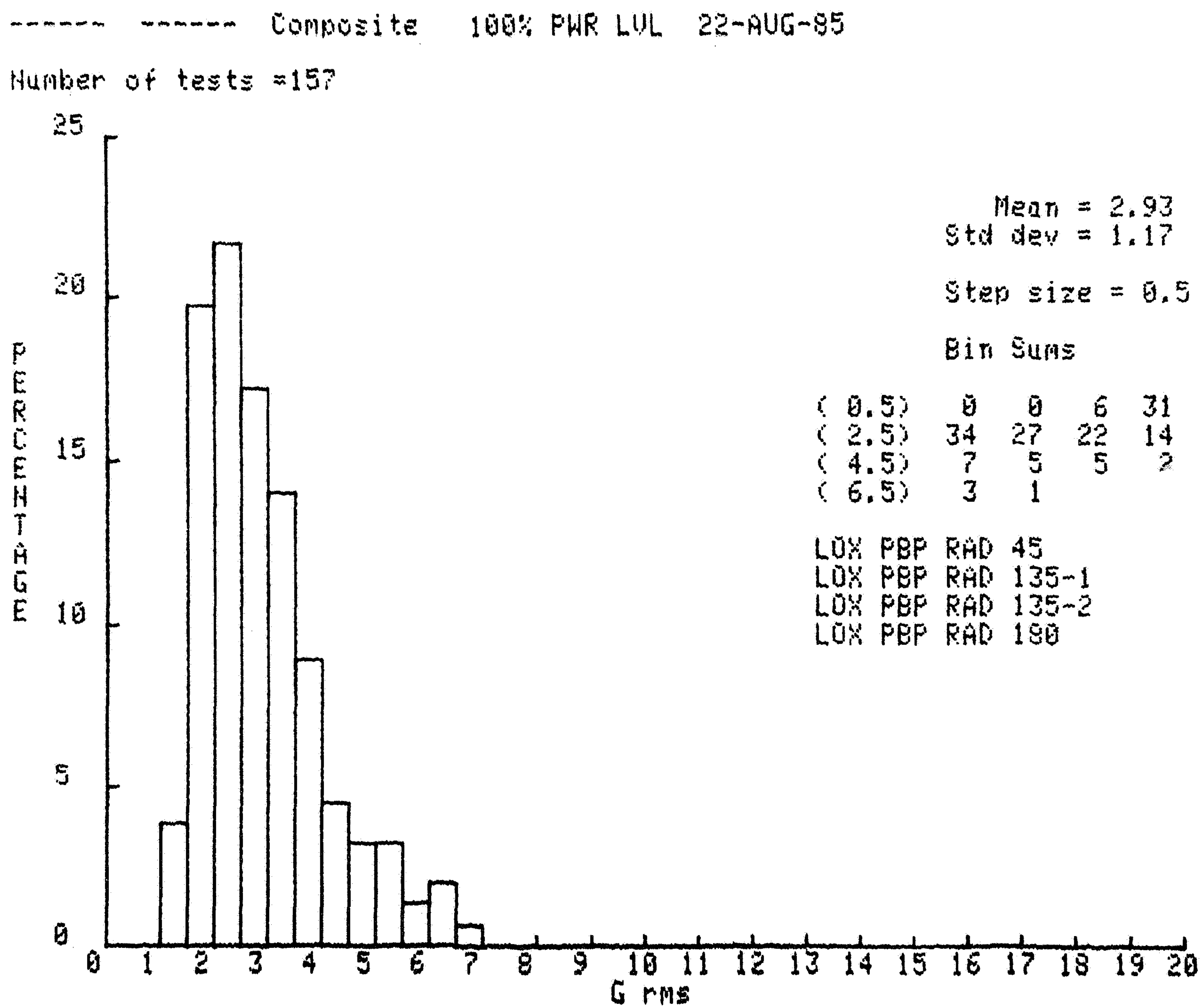

Figure 69. Probability Density of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

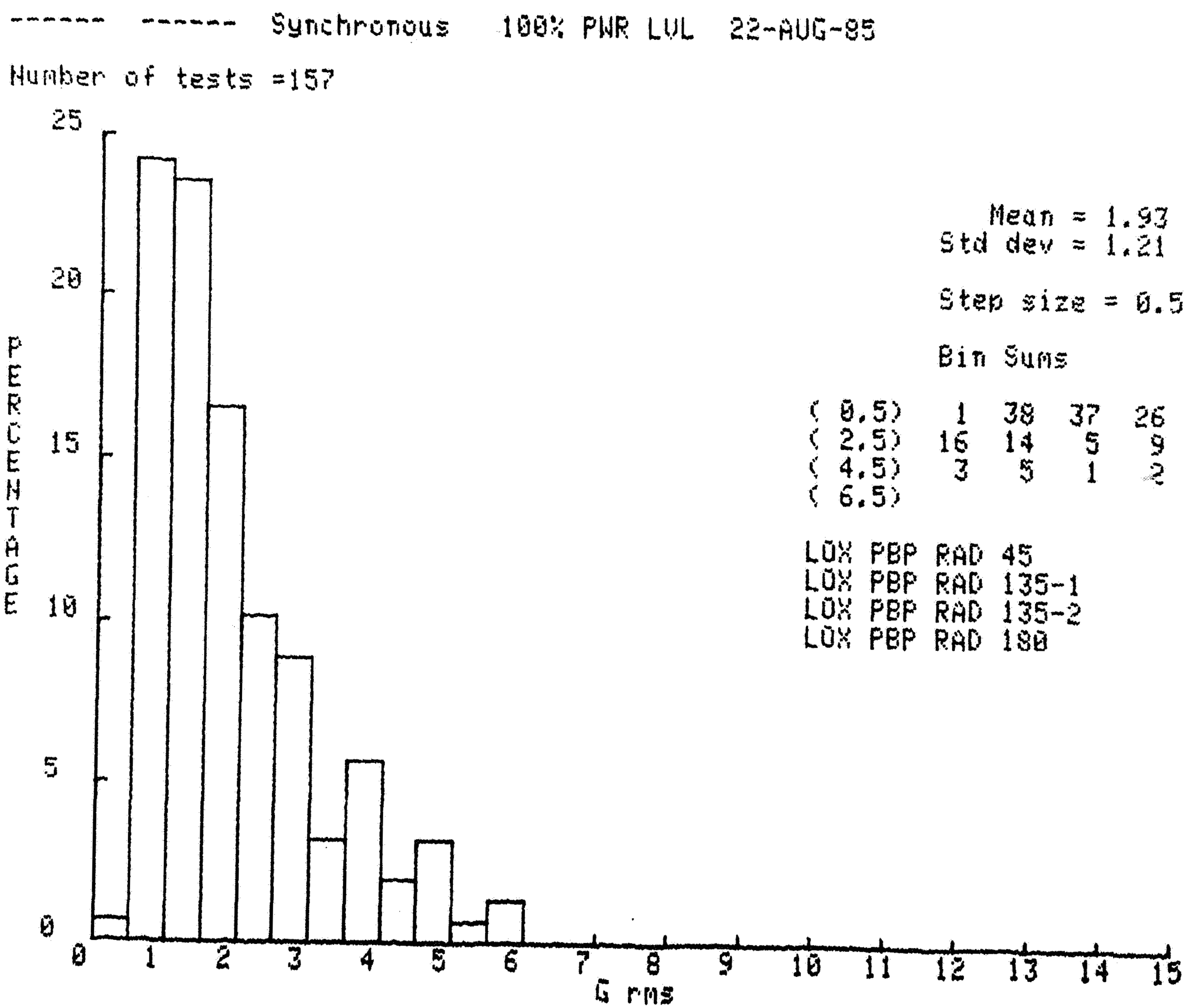

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Figure 70. Probability Density of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 100% Power Level During Flight

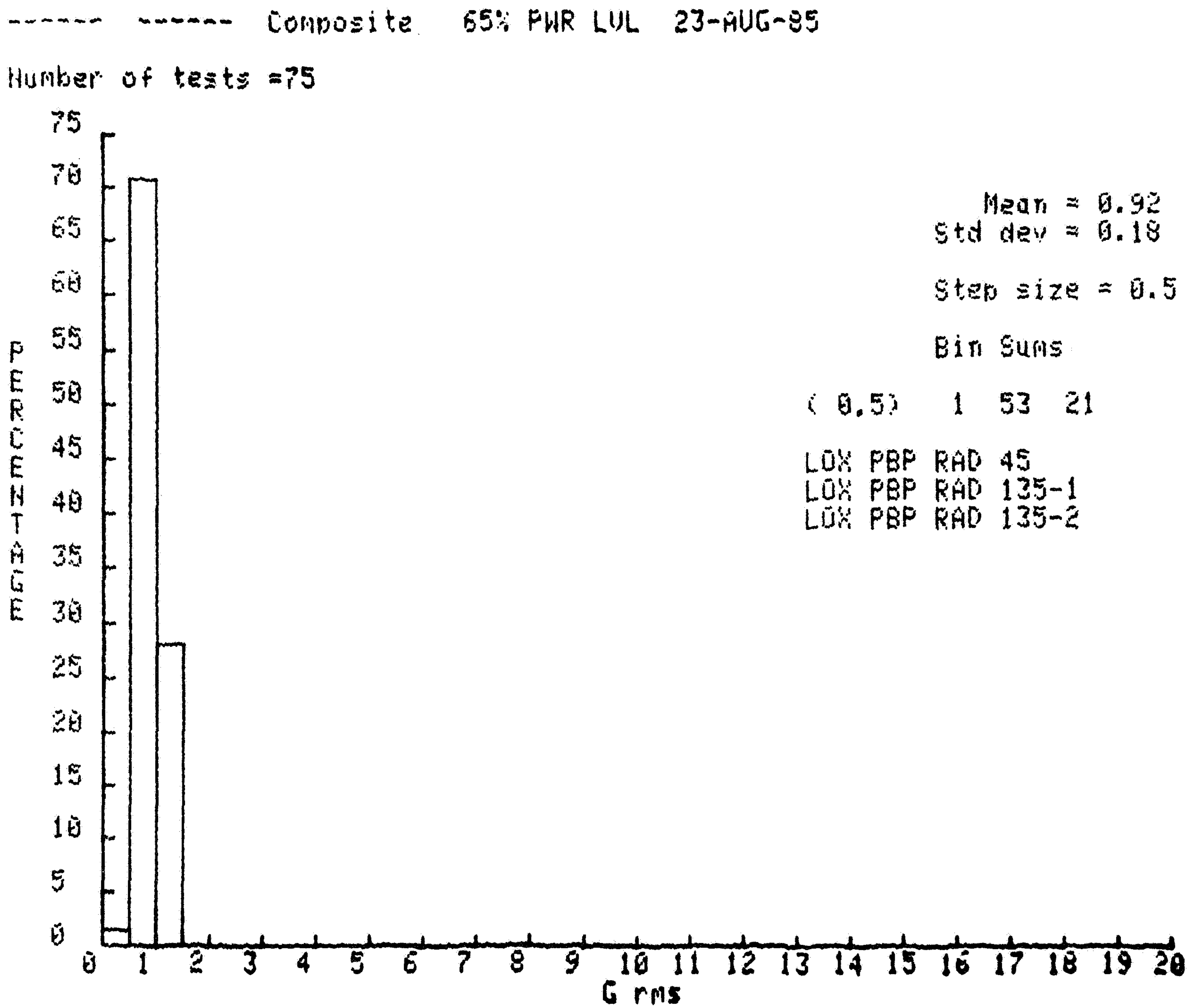

Figure 71. Probability Density of Composite Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

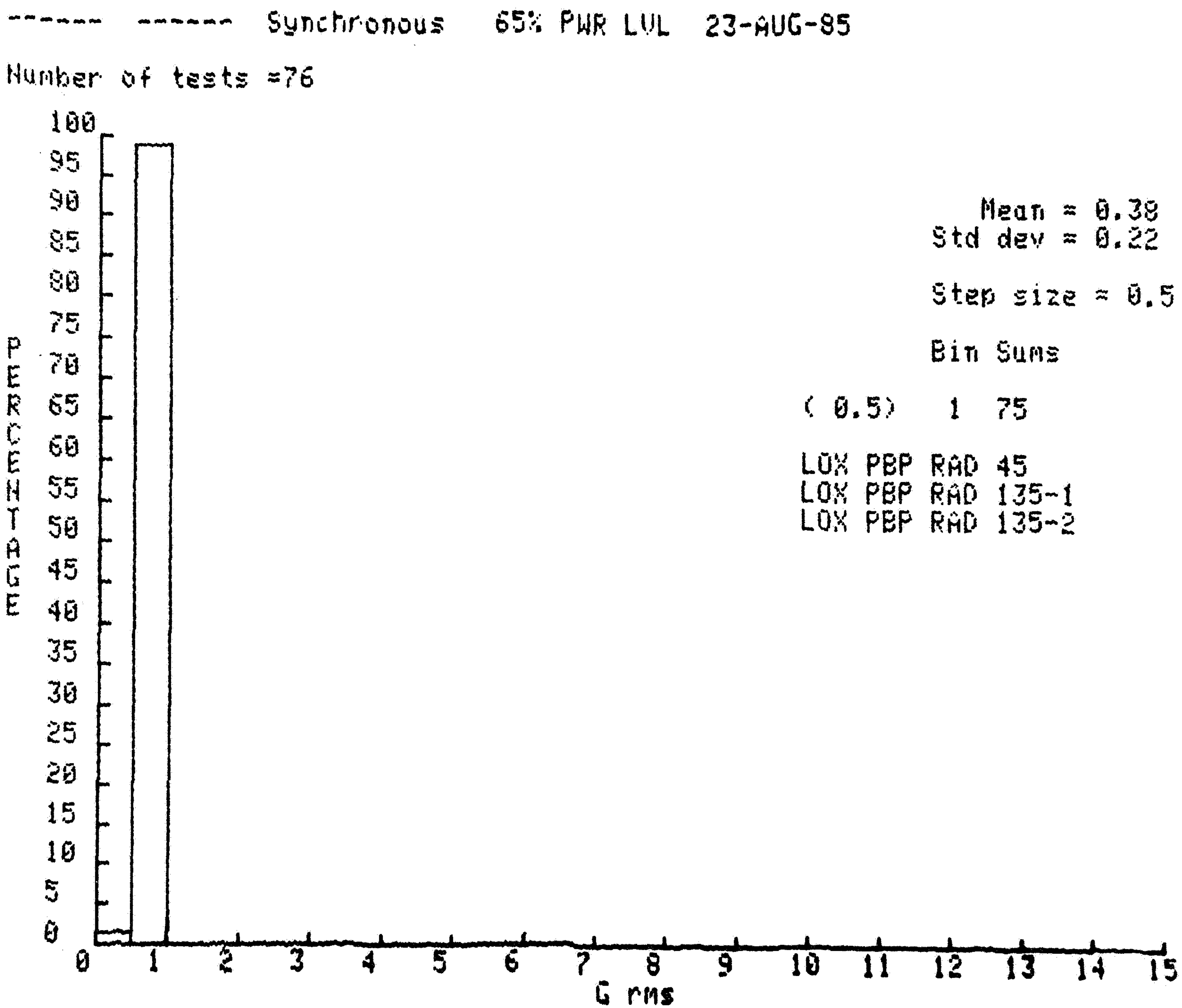

Figure 72. Probability Density of Synchronous Vibration Levels on the High Pressure Oxidizer Turbopump at 65% Power Level During Flight

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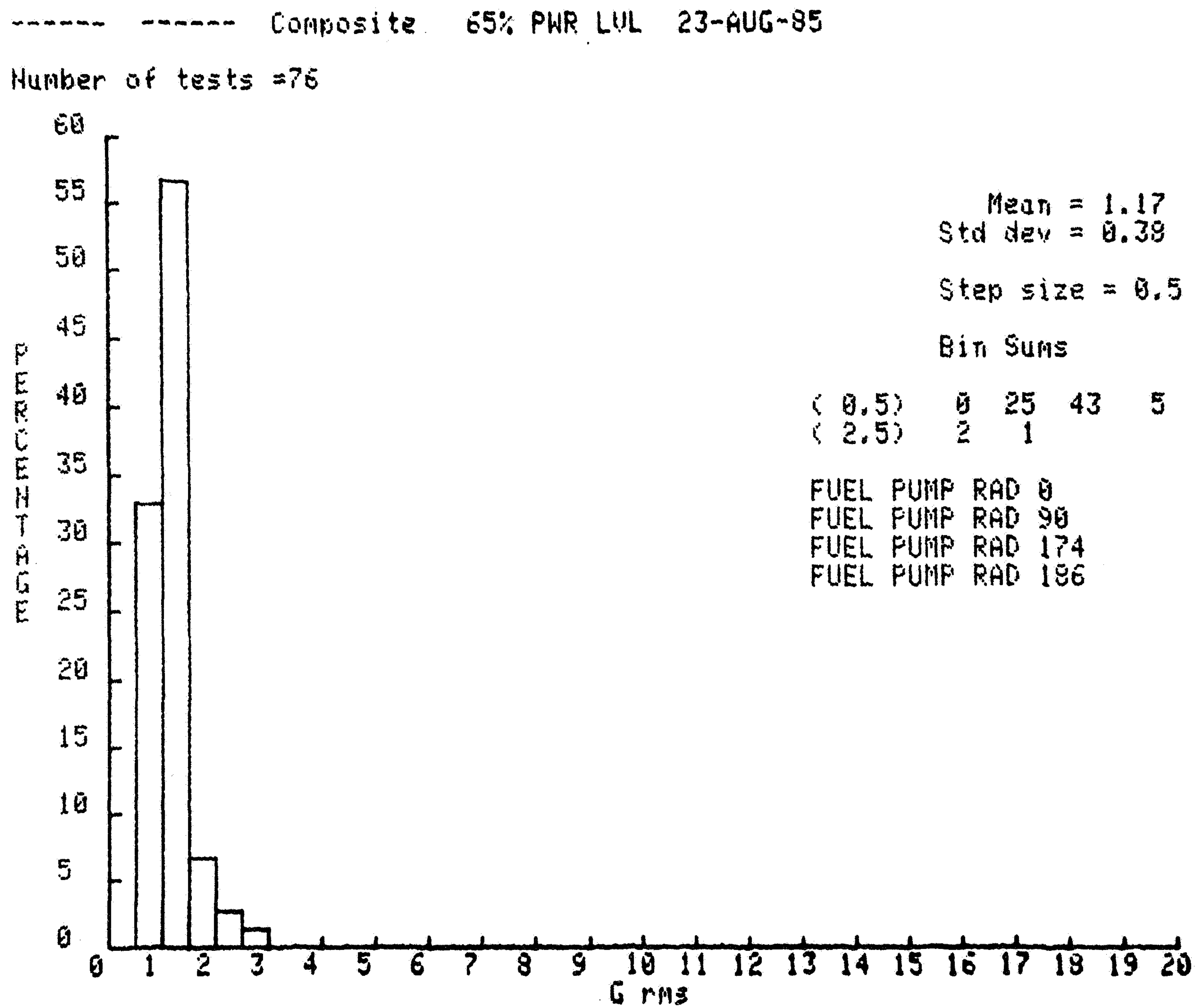

Figure 73. Probability Density of Composite Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

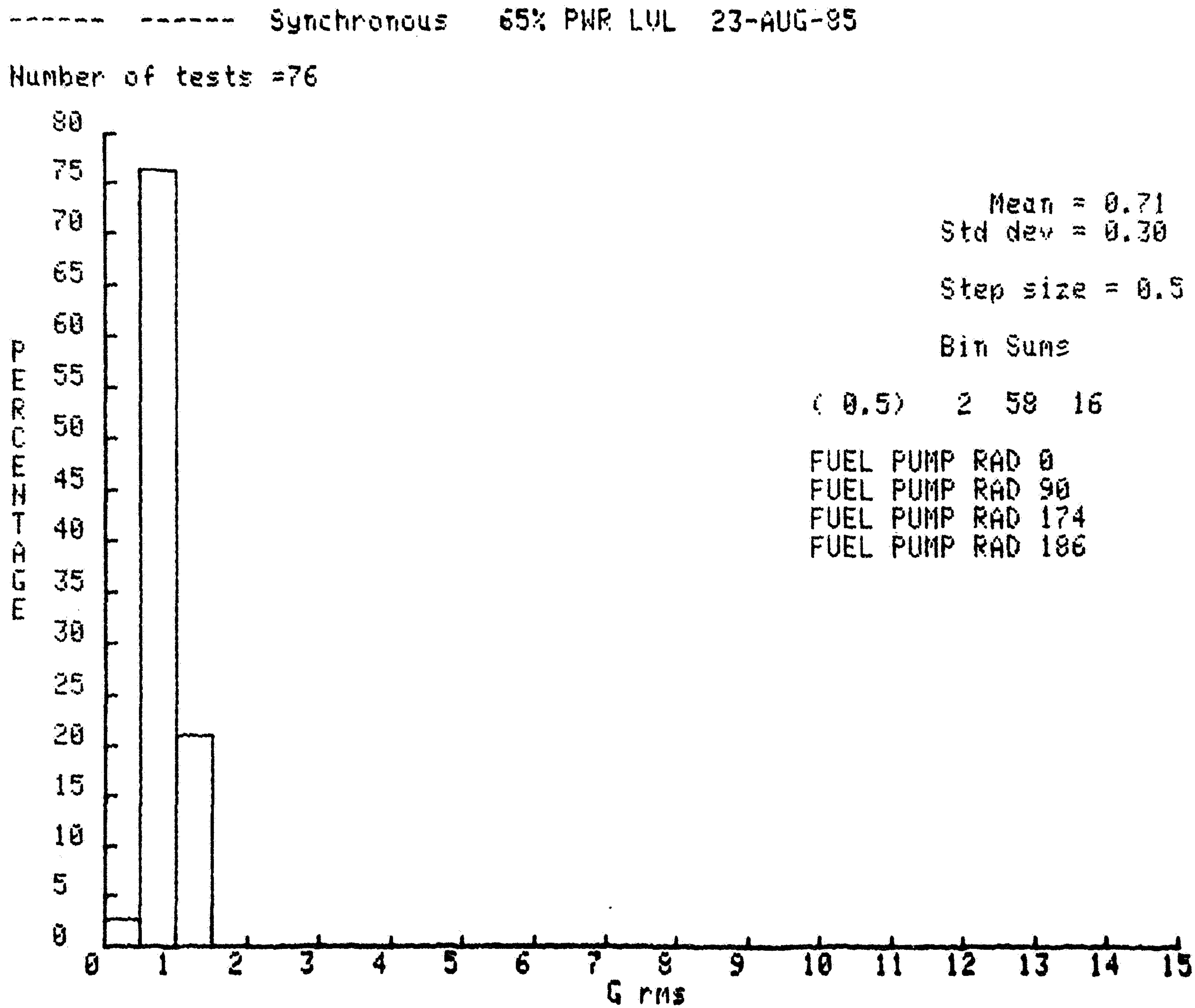

Figure 74. Probability Density of Synchronous Vibration Levels on the High Pressure Fuel Turbopump at 65% Power Level During Flight

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FLIGHT DATA SHEETS

HPFTP

104% POWER LEVEL

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HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	9110	2315	2213	2315	9211	2213
TEST NUMBER	STS06E1	STS06E2	STS06E3	STS07E1	STS07E2	STS07E3
PWR LVL/SYNC FREQ	104%/596	104%/601	104%/596	104%/601	104%/601	104%/596
PUMP RAD (0)						
Composite				2.5	4.8	3.8
Synchronous				2.1	4.5	3.4
PUMP RAD (90)		(noisy)				
Composite	1.8	1.0	3.0			
Synchronous	1.2	0.4	2.3			
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)		(noisy)				
Composite	2.2	4.4	3.2	1.8	5.2	4.0
Synchronous	1.8	1.6	3.0	1.3	5.0	3.5
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

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HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	5101R1	2018	2116R3	2020R1	2017R1	4001R1
TEST NUMBER	STS13E1	STS13E2	STS13E3	STS41DE1	STS41DE2	STS41DE3
PWR LVL/SYNC FREQ	104%/588	104%/588	104%/598	104%/590	104%/590	104%/590
PUMP RAD (0)						
Composite	1.5	2.4	5.0	2.4	3.8	2.1
Synchronous	1.2	2.2	4.7	2.1	3.5	1.6
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite				2.8	3.8	2.5
Synchronous				2.4	3.4	2.0
PUMP RAD (186)						
Composite	1.1	2.2	4.2	3.2	3.3	2.2
Synchronous	0.9	2.0	3.7	2.6	2.9	1.8
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	2020R1	2017R2	2118	2515R1	9311R1	2216
TEST NUMBER	STS51AE1	STS51AE2	STS51AE3	STS51BE1	STS51BE2	STS51BE3
PWR LVL/SYNC FREQ	104%/590	104%/588	104%/593	104%/585	104%/598	104%/590
PUMP RAD (0)						
Composite	3.8	3.7	3.0	2.0	1.4	2.6
Synchronous	3.5	3.5	2.7	1.7	0.9	2.1
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)			(noisy)		(?)	
Composite	3.8	3.3	7.3	1.6	1.7	2.8
Synchronous	3.6	3.2	2.6	1.4	1.1	2.4
PUMP RAD (186)					(?)	
Composite	5.1	3.5	2.6	1.6	2.5	2.5
Synchronous	4.7	3.3	2.3	1.3	0.8	2.0
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	4202	2017R2	4003	2515R1	4202R1	2216
TEST NUMBER	STS51CE1	STS51CE2	STS51CE3	STS51FE1	$TS51FE2	STS51FE3
PWR LVL/SYNC FREQ	104%/588	104%/588	104%/593	104%/585	104%/585	104%/593
PUMP RAD (0)						
Composite	3.4	2.2	2.9	2.0	3.5	3.0
Synchronous	3.3	1.8	2.6	1.7	3.2	2.7
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)			(noisy)			
Composite	3.1	2.0	5.8	2.6	3.1	2.7
Synchronous	3.0	1.7	3.5	1.7	3.0	2.5
PUMP RAD (186)						
Composite	3.2	1.9	3.3	2.5	3.2	2.5
Synchronous	3.1	1.6	3.0	1.9	3.0	2.0
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	2121	4201R2	4003R1			
TEST NUMBER	STS51GE1	STS51GE2	STS51GE3			
PWR LVL/SYNC FREQ	104%/590	104%/593	104%/593			
PUMP RAD (0)						
Composite	3.2	2.6	4.5			
Synchronous	2.9	2.4	4.3			
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite	3.3	2.6	5.7			
Synchronous	3.0	2.2	3.8			
PUMP RAD (186)						
Composite	3.0	2.7	3.4			
Synchronous	2.7	2.3	3.3			
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

FLIGHT DATA SHEETS

HPOTP

104% POWER LEVEL

HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	9010	2015	2016	9010	2015	2016
TEST NUMBER	STS06E1	STS06E2	STS06E3	STS07E1	STS07E2	STS07E3
PWR LVL/SYNC FREQ	104%/469	104%/479	104%/474	104%/469	104%/479	104%/474
PUMP RAD (45)						
Composite	4.3	2.5	2.0	3.2	3.5	2.0
Synchronous	3.9	1.4	1.3	2.5	2.5	1.2
PUMP RAD (135-1)						
Composite	4.7			3.0		2.2
Synchronous	3.0			2.7		1.3
PUMP RAD (135-2)						
Composite		2.5	2.5		3.0	
Synchronous		1.5	1.5		2.3	
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2020	2021	2016	2020	9211	4001
TEST NUMBER	STS13E1	STS13E2	STS13E3	STS41DE1	STS41DE2	STS41DE3
PWR LVL/SYNC FREQ	104%/472	104%/473	104%/462	104%/475	104%/478	104%/469
PUMP RAD (45)						
Composite	1.9	2.4	2.0	2.0	2.4	2.6
Synchronous	0.9	0.8	1.4	1.2	1.4	1.3
PUMP RAD (135-1)						
Composite	2.4	2.6	2.5	2.1	3.1	2.2
Synchronous	1.5	2.1	1.4	1.6	2.2	1.2
PUMP RAD (135-2)						
Composite				2.5	2.9	---
Synchronous				1.8	2.3	1.2
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2020	9211	9110	2019R1	2021	4001
TEST NUMBER	STS51AE1	STS51AE2	STS51AE3	STS51BE1	STS51BE2	STS51BE3
PWR LVL/SYNC FREQ	104%/473	104%/478	104%/475	104%/470	104%/468	104%/468
PUMP RAD (45)						
Composite	2.0	2.5	4.7	2.3	2.0	2.3
Synchronous	1.2	1.2	2.1	1.6	1.1	1.4
PUMP RAD (135-1)						
Composite	2.7	3.0	4.0	2.4	3.5	2.2
Synchronous	2.3	2.0	3.2	1.6	3.0	0.8
PUMP RAD (135-2)						
Composite	3.0	3.0	3.2	2.2	3.2	Bad
Synchronous	2.5	2.2	2.7	1.3	2.6	Bad
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2020	2018R1	9110	2019R2	4003R2	4001R1
TEST NUMBER	STS51CE1	STS51CE2	STS51CE3	STS51FE1	$TS51FE2	STS51FE3
PWR LVL/SYNC FREQ	104%/475	104%/475	104%/475	104%/470	104%/470	104%/463
PUMP RAD (45)						
Composite	1.8	1.5	4.4	2.6	2.6	3.6
Synchronous	1.0	0.8	2.0	1.7	0.9	1.4
PUMP RAD (135-1)						
Composite	2.3	2.5	4.0	2.3	2.2	2.4
Synchronous	1.2	1.0	3.2	1.4	0.9	0.5
PUMP RAD (135-2)						
Composite	2.2	2.9	3.0	2.1	3.3	3.1
Synchronous	1.4	1.2	2.6	1.1	0.9	0.6
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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PUMP SERIAL #	2115	2016R3	9110			
TEST NUMBER	STS51GE1	STS51GE2	STS51GE3			
PWR LVL/SYNC FREQ	104%/470	104%/465	104%/473			
PUMP RAD (45)						
Composite	1.8	2.4	4.3			
Synchronous	0.6	0.7	2.3			
PUMP RAD (135-1)						
Composite	2.1	2.4	4.4			
Synchronous	1.4	1.8	3.4			
PUMP RAD (135-2)						
Composite	2.4	3.8	3.6			
Synchronous	1.4	2.0	2.6			
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

FLIGHT DATA SHEETS

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100% POWER LEVEL

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	9006R1	0306R1	0009R1	9006R1	0306R1	0009R1
TEST NUMBER	STS01E1	STS01E2	STS01E3	STS02E1	STS02E2	STS02E3
PWR LVL/SYNC FREQ	100%/581	100%/581	100%/581	100%/576	100%/576	100%/581
PUMP RAD (0)						
Composite						
Synchronous						
PUMP RAD (90)						
Composite				4.8	2.3	3.5
Synchronous				4.5	0.8	2.1
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)						
Composite	6.2	2.2	3.2	7.2	1.8	3.5
Synchronous	5.6	1.8	2.0	5.8	0.5	2.7
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	9006R1	0306R1	0009R1	2009	0306R1	0009R1
TEST NUMBER	STS03E1	STS03E2	STS03E3	STS04E1	STS04E2	STS04E3
PWR LVL/SYNC FREQ	100%/581	100%/576	100%/581	100%/581	100%/576	100%/581
PUMP RAD (0)						
Composite						
Synchronous						
PUMP RAD (90)		(noisy)				
Composite	4.1	2.3	4.0	4.0	Bad	3.1
Synchronous	4.0	1.3	2.5	2.9	Bad	2.5
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)					(noisy)	
Composite	7.0	1.8	2.8	4.5	2.0	3.1
Synchronous	6.4	1.2	2.3	3.9	0.7	2.1
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

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PUMP SERIAL #	2009	0306R2	9006R2	9110	2315	2213
TEST NUMBER	STS05E1	STS05E2	STS05E3	STS06E1	STS06E2	STS06E3
PWR LVL/SYNC FREQ	100%/586	100%/581	100%/576	100%/581	100%/586	100%/581
PUMP RAD (0)						
Composite						
Synchronous						
PUMP RAD (90)		(noisy)			(noisy)	
Composite	4.5	5.0	5.0	1.6	---	2.1
Synchronous	3.5	2.0	4.3	0.9	---	1.9
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)		(noisy)			(noisy)	
Composite	4.9	2.3	7.0	1.4	2.0	2.6
Synchronous	4.3	1.3	5.8	1.1	0.5	2.4
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

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PUMP SERIAL #	2315	9211	2213	2315	9211	2116R2
TEST NUMBER	STS07E1	STS07E2	STS07E3	STS08E1	STS08E2	STS08E3
PWR LVL/SYNC FREQ	100%/581	100%/581	100%/581	100%/581	100%/581	100%/581
PUMP RAD (0)						
Composite	1.1	3.1	2.7	2.0	3.5	5.3
Synchronous	0.8	2.8	2.5	1.8	3.3	5.2
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)						
Composite	1.0	2.8	3.2	1.9	3.8	4.3
Synchronous	0.7	2.5	2.9	1.2	3.4	4.1
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	5101R1	9211	2116R2	5101R1	2018	2116R3
TEST NUMBER	STS11E1	STS11E2	STS11E3	STS13E1	STS13E2	STS13E3
PWR LVL/SYNC FREQ	100%/575	100%/582	100%/582	100%/575	100%/573	100%/580
PUMP RAD (0)						
Composite	1.4	3.3	4.8	1.5	1.7	3.3
Synchronous	1.2	3.1	4.2	1.1	1.3	2.8
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite						
Synchronous						
PUMP RAD (186)						
Composite	1.3	3.7	4.4	1.2	1.7	2.6
Synchronous	1.0	3.4	3.8	1.0	1.3	2.3
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

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PUMP SERIAL #	2020R1	2017R1	4001R1	2515R1	9311R1	4001R1
TEST NUMBER	STS41DE1	STS41DE2	STS41DE3	STS41GE1	STS41GE2	STS41GE3
PWR LVL/SYNC FREQ	100%/575	100%/573	100%/575	100%/570	100%/583	100%/575
PUMP RAD (0)						
Composite	1.4	1.3	1.2	1.9	1.8	2.8
Synchronous	1.0	1.0	0.8	1.6	1.6	2.5
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)					(noisy)	
Composite	1.8	1.3	2.1	1.8	7.2	2.9
Synchronous	1.4	1.0	1.6	1.6	3.4	2.6
PUMP RAD (186)					(?)	
Composite	2.4	1.5	1.5	1.8	2.5	2.5
Synchronous	1.7	1.0	1.0	1.5	0.6	2.3
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	2020R1	2017R2	2118	2515R1	9311R1	2216
TEST NUMBER	STS51AE1	STS51AE2	STS51AE3	STS51BE1	STS51BE2	STS51BE3
PWR LVL/SYNC FREQ	100%/575	100%/573	100%/580	100%/568	100%/583	100%/575
PUMP RAD (0)						
Composite	1.9	1.5	1.6	1.8	1.5	2.1
Synchronous	1.5	1.2	1.2	1.5	1.0	1.5
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)					(?)	
Composite	1.7	1.3	2.4	1.7	1.1	1.6
Synchronous	1.3	1.0	1.1	1.5	0.7	1.2
PUMP RAD (186)					(?)	
Composite	3.1	1.1	1.5	1.6	1.7	1.9
Synchronous	2.4	0.8	1.2	1.4	0.4	1.4
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	4202	2017R2	4003	4202	2017R2	4003
TEST NUMBER	STS51CE1	STS51CE2	STS51CE3	STS51DE1	STS51DE2	STS51DE3
PWR LVL/SYNC FREQ	100%/573	100%/573	100%/579	100%/575	100%/573	100%/587
PUMP RAD (0)						
Composite	2.7	2.2	2.4	3.2	3.0	2.7
Synchronous	2.5	2.0	2.1	2.9	2.7	2.4
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						(noisy)
Composite	2.4	1.8	Bad	3.1	2.7	4.7
Synchronous	2.3	1.7	Bad	2.8	2.4	2.3
PUMP RAD (186)						
Composite	2.8	1.7	2.9	3.2	2.4	2.8
Synchronous	2.7	1.6	2.5	2.9	2.1	2.5
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

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PUMP SERIAL #	2515R1	4202R1	2216	2121	4201R2	4003R1
TEST NUMBER	STS51FE1	*TS51FE2	STS51FE3	STS51GE1	STS51GE2	STS51GE3
PWR LVL/SYNC FREQ	100%/568	100%/570	100%/575	100%/575	100%/575	100%/578
PUMP RAD (0)						
Composite	1.7	2.2	1.7	1.8	2.4	3.2
Synchronous	1.4	1.9	1.1	1.5	2.2	2.9
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite	2.1	2.0	1.4	1.7	2.2	6.1
Synchronous	1.6	1.7	0.7	1.5	2.0	2.7
PUMP RAD (186)						
Composite	1.9	2.3	1.6	2.0	2.0	2.4
Synchronous	1.4	2.0	0.7	1.7	1.8	2.1
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

FLIGHT DATA SHEETS

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100% POWER LEVEL

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PUMP SERIAL #	0007R1	2404	2105	0007R1	2404	2105
TEST NUMBER	STS01E1	STS01E2	STS01E3	STS02E1	STS02E2	STS02E3
PWR LVL/SYNC FREQ	100%/464	100%/464	100%/469	100%/464	100%/469	100%/464
PUMP RAD (45)						
Composite	4.0	2.5	3.0	4.8	2.5	3.2
Synchronous	3.9	2.1	1.2	4.3	2.0	1.0
PUMP RAD (135-1)						
Composite	4.2	3.8	4.9	5.2	3.4	4.1
Synchronous	4.0	3.2	3.8	5.0	3.1	1.8
PUMP RAD (135-2)						
Composite	5.0	3.5	4.5	5.3	3.5	3.4
Synchronous	4.1	3.1	3.9	5.0	3.0	1.8
PUMP RAD (180)						
Composite	3.9	3.0	3.1	3.5	3.0	3.0
Synchronous	3.0	1.2	2.1	3.0	1.5	1.5
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	0007R1	2404	2105R1	0007R1	2404	2105R1
TEST NUMBER	STS03E1	STS03E2	STS03E3	STS04E1	STS04E2	STS04E3
PWR LVL/SYNC FREQ	100%/464	100%/469	100%/469	100%/464	100%/469	100%/469
PUMP RAD (45)			(noisy)			(noisy)
Composite	5.8	3.0	4.8	7.0	3.1	4.0
Synchronous	5.0	2.6	2.0	6.0	2.5	2.0
PUMP RAD (135-1)			(noisy)			
Composite	5.5	3.8	3.8	6.5	4.0	Bad
Synchronous	5.0	3.7	1.3	5.9	3.8	Bad
PUMP RAD (135-2)			(noisy)			
Composite	5.3	3.7	3.2	6.0	3.9	Bad
Synchronous	4.7	3.3	1.4	5.3	3.3	Bad
PUMP RAD (180)		(noisy)			(noisy)	
Composite	4.1	3.0	2.5	4.9	3.1	2.7
Synchronous	3.6	1.4	1.5	4.1	1.4	2.0
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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PUMP SERIAL #	9009R3	2404	2105R1	9010	2015	2016
TEST NUMBER	STS05E1	STS05E2	STS05E3	STS06E1	STS06E2	STS06E3
PWR LVL/SYNC FREQ	100%/469	100%/469	100%/469	100%/449	100%/459	100%/454
PUMP RAD (45)			(noisy)			
Composite	2.6	3.0	4.1	2.7	2.1	1.8
Synchronous	1.9	2.5	1.7	2.1	1.2	0.8
PUMP RAD (135-1)	(noisy)		(noisy)			
Composite	2.5	4.1	3.2	3.2		
Synchronous	1.9	3.8	1.6	3.0		
PUMP RAD (135-2)			(noisy)			
Composite	3.0	4.0	6.5		2.2	2.1
Synchronous	2.0	3.6	2.0		1.2	1.2
PUMP RAD (180)	(noisy)	(noisy)	(noisy)			
Composite	2.8	3.2	5.5			
Synchronous	---	1.4	1.5			
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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PUMP SERIAL #	9010	2015	2016	2016	2016	2016
TEST NUMBER	STS07E1	STS07E2	STS07E3	STS08E1	STS08E2	STS08E3
PWR LVL/SYNC FREQ	100%/449	100%/454	100%/454	100%/449	100%/459	100%/449
PUMP RAD (45) Composite Synchronous	2.2 1.7	2.3 1.3	1.7 0.6	3.1 2.6	2.1 1.4	2.0 1.1
PUMP RAD (135-1) Composite Synchronous	2.7 2.5		1.8 0.8	3.0 2.7	2.1 1.4	2.2 1.5
PUMP RAD (135-2) Composite Synchronous		2.1 1.2				
PUMP RAD (180) Composite Synchronous						
PUMP RAD (225) Composite Synchronous						
TURB. RAD (45) Composite Synchronous						
TURB. RAD (90) Composite Synchronous						
TURB. RAD (135) Composite Synchronous						

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PUMP SERIAL #	2020	2015	2016	2020	2021	2016
TEST NUMBER	STS11E1	STS11E2	STS11E3	STS13E1	STS13E2	STS13E3
PWR LVL/SYNC FREQ	100%/455	100%/452	*100%/457	100%/458	100%/455	100%/452
PUMP RAD (45)						
Composite	1.4	3.2	1.4	1.5	2.0	1.7
Synchronous	0.6	2.5	0.6	0.7	0.6	0.6
PUMP RAD (135-1)						
Composite	1.2	2.0	1.2	1.5	2.3	1.7
Synchronous	0.8	1.6	0.8	0.9	1.7	0.8
PUMP RAD (135-2)						
Composite						
Synchronous						
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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PUMP SERIAL #	2020	9211	4001	2019R1	2021	4001
TEST NUMBER	STS41DE1	STS41DE2	STS41DE3	STS41GE1	STS41GE2	STS41GE3
PWR LVL/SYNC FREQ	100%/455	100%/460	100%/450	100%/455	100%/455	100%/455
PUMP RAD (45)						
Composite	1.8	2.3	2.2	1.8	2.0	2.4
Synchronous	1.0	1.6	0.7	1.2	0.9	0.9
				ss=0.4	ss=0.9	ss=0.8
PUMP RAD (135-1)						
Composite	2.1	2.7	1.8	1.7	2.5	1.9
Synchronous	1.6	2.0	0.7	0.9	2.1	0.9
				ss=0.4	ss=0.5	ss=0.5
PUMP RAD (135-2)						(noisy)
Composite	2.3	2.8	---	1.5		6.2
Synchronous	1.7	2.3	1.3	0.7		1.4
				ss=0.3		
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2020	9211	9110	2019R1	2021	4001
TEST NUMBER	STS51AE1	STS51AE2	STS51AE3	STS51BE1	STS51BE2	STS51BE3
PWR LVL/SYNC FREQ	100%/458	100%/460	100%/458	100%/455	100%/453	100%/453
PUMP RAD (45)						
Composite	1.8	2.7	3.8	2.1	2.1	2.3
Synchronous	0.9	2.0	2.1	1.3	1.0	0.9
				ss=0.6	ss=1	ss=0.4
PUMP RAD (135-1)						
Composite	2.1	3.3	3.1	1.9	2.7	2.0
Synchronous	1.7	2.5	2.5	1.1	2.2	0.7
				ss=0.5	ss=0.6	ss=0.4
PUMP RAD (135-2)						
Composite	2.3	3.2	2.7	1.8	2.7	Bad
Synchronous	1.8	2.6	2.3	0.9	1.9	Bad
				ss=0.7	ss=0.6	
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2020	2019R1	9110	2115	2019R1	9110
TEST NUMBER	STS51CE1	STS51CE2	STS51CE3	STS51DE1	STS51DE2	STS51DE3
PWR LVL/SYNC FREQ	100%/458	100%/458	100%/458	100%/453	100%/455	100%/458
PUMP RAD (45)						
Composite	1.8	1.7	4.1	1.8	1.7	3.7
Synchronous	1.0	0.7	2.4	0.9	0.7	1.9
	ss=0.2	ss=0.8			ss=0.8	
PUMP RAD (135-1)						
Composite	1.7	2.3	3.2	2.4	2.6	3.5
Synchronous	1.1	1.1	2.6	1.8	1.3	2.8
	ss=0.2	ss=0.6			ss=0.9	
PUMP RAD (135-2)						
Composite	1.9	2.4	2.8	2.5	2.7	3.1
Synchronous	1.2	1.1	2.4	1.7	1.2	2.6
	ss=0.2	ss=0.6			ss=0.7	
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

DATA COMPARISON *=early co

PUMP SERIAL #	2019R2	4003R2	4001R1	2115	2016R3	9110
TEST NUMBER	STS51FE1	*TS51FE2	STS51FE3	STS51GE1	STS51GE2	STS51GE3
PWR LVL/SYNC FREQ	100%/455	100%/455	100%/450	100%/450	100%/453	100%/459
PUMP RAD (45)						
Composite	2.4	2.2	3.0	1.6	2.0	3.8
Synchronous	1.4	0.7	0.7	0.6	0.3	2.2
	ss=0.6	ss=0.6	ss=0.8			
PUMP RAD (135-1)						
Composite	1.9	1.9	2.0	1.8	2.0	3.7
Synchronous	1.0	0.6	0.4	1.3	1.3	2.8
	ss=0.5	ss=0.6	ss=0.7			
PUMP RAD (135-2)						
Composite	1.8	2.7	2.4	2.1	2.8	3.2
Synchronous	0.8	0.6	0.5	1.3	1.5	2.5
	ss=0.5	ss=0.5	ss=0.7			
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

APPENDIX A

VIBRATION DATA FROM STS LAUNCH 27 (51-I) AND 28 (51-J)

```
TESTS USED IN THIS ANALYSIS:

TEST #'S STS01,STS02,STS03,STS04,STS05,STS16,STS07,STS08,STS11,STS13,STS
41D,STS41G,STS51A,STS51B,STS51C,STS51D,STS51F,STS51G,STS51I,STS51J,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

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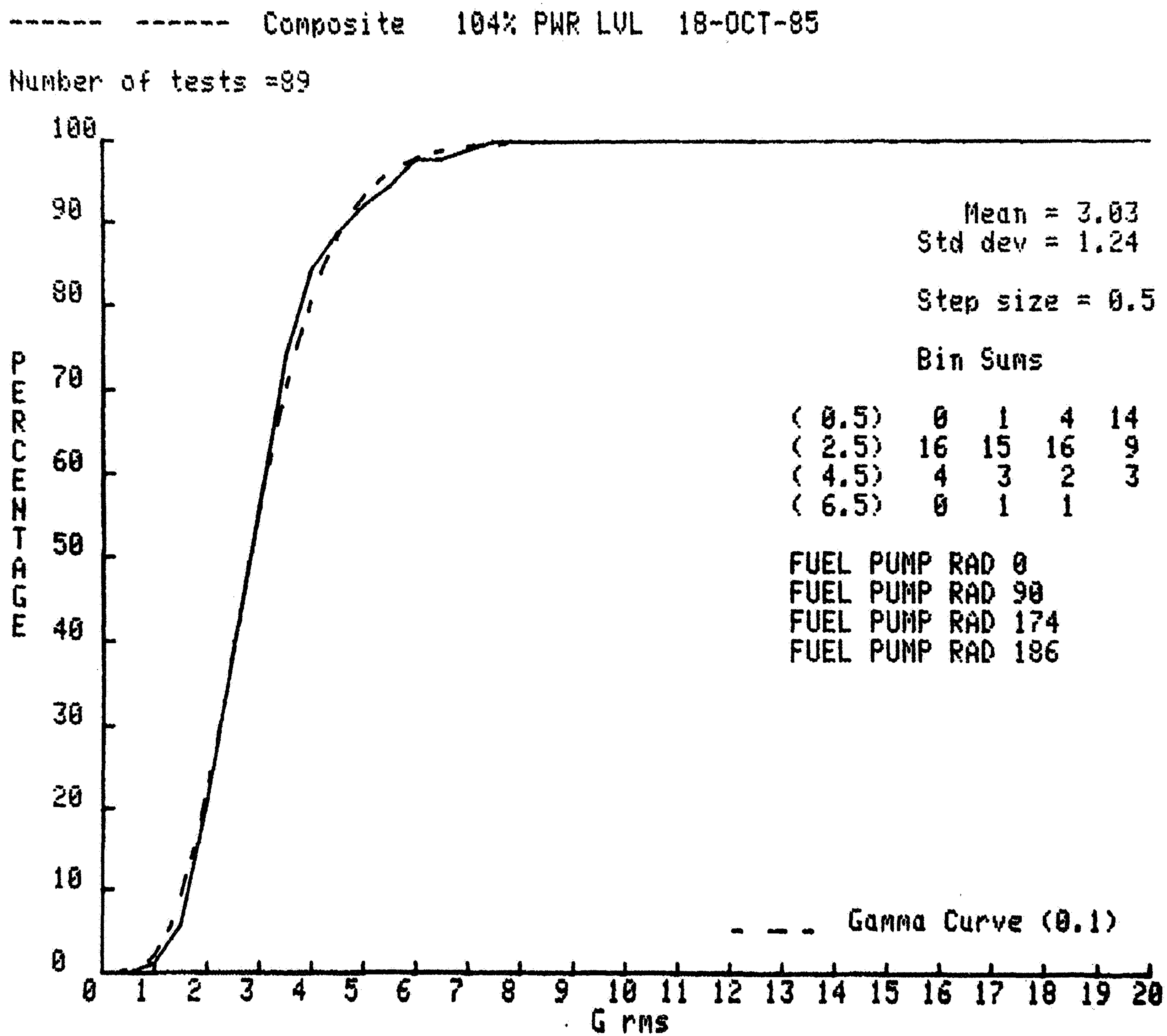
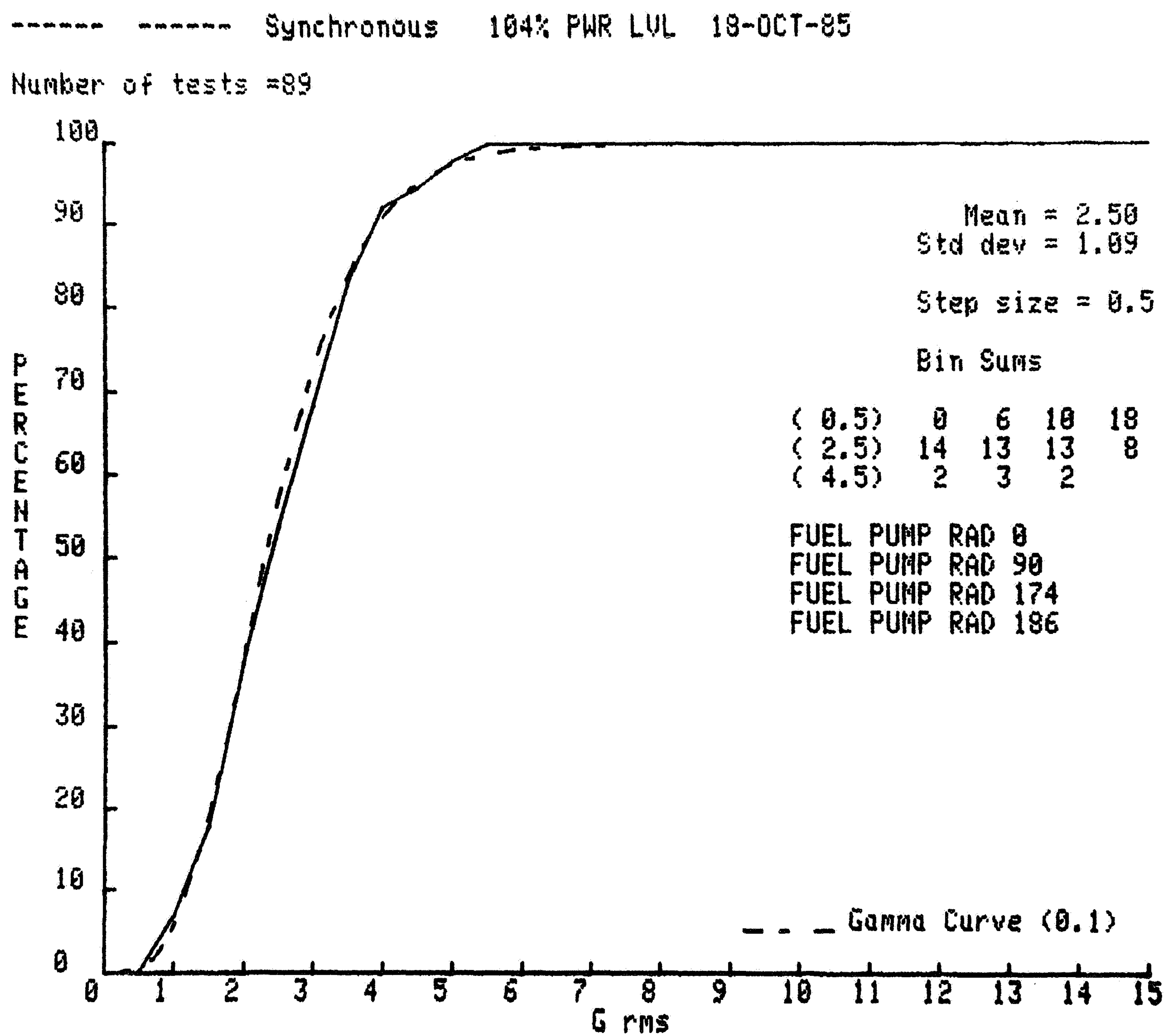
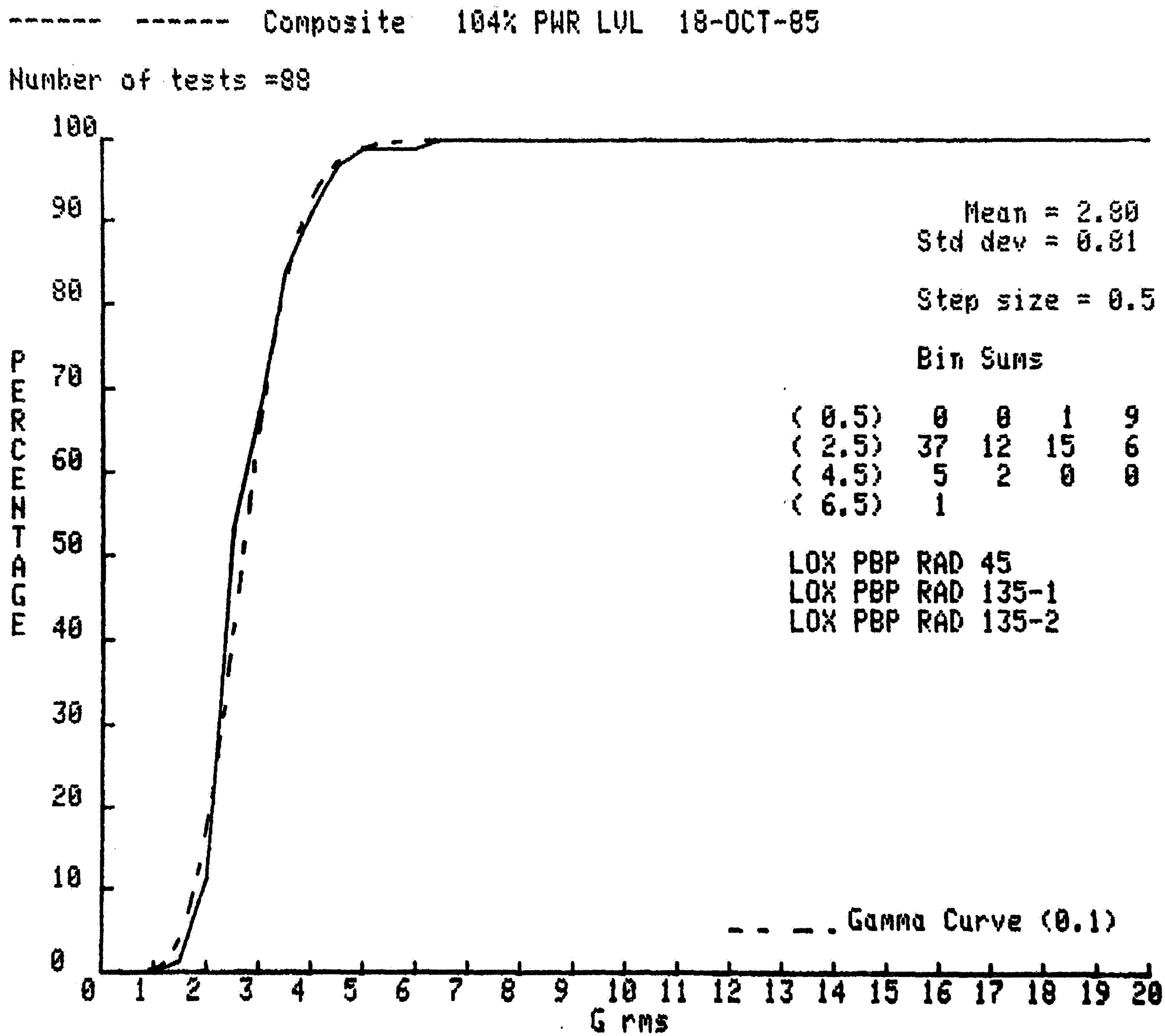
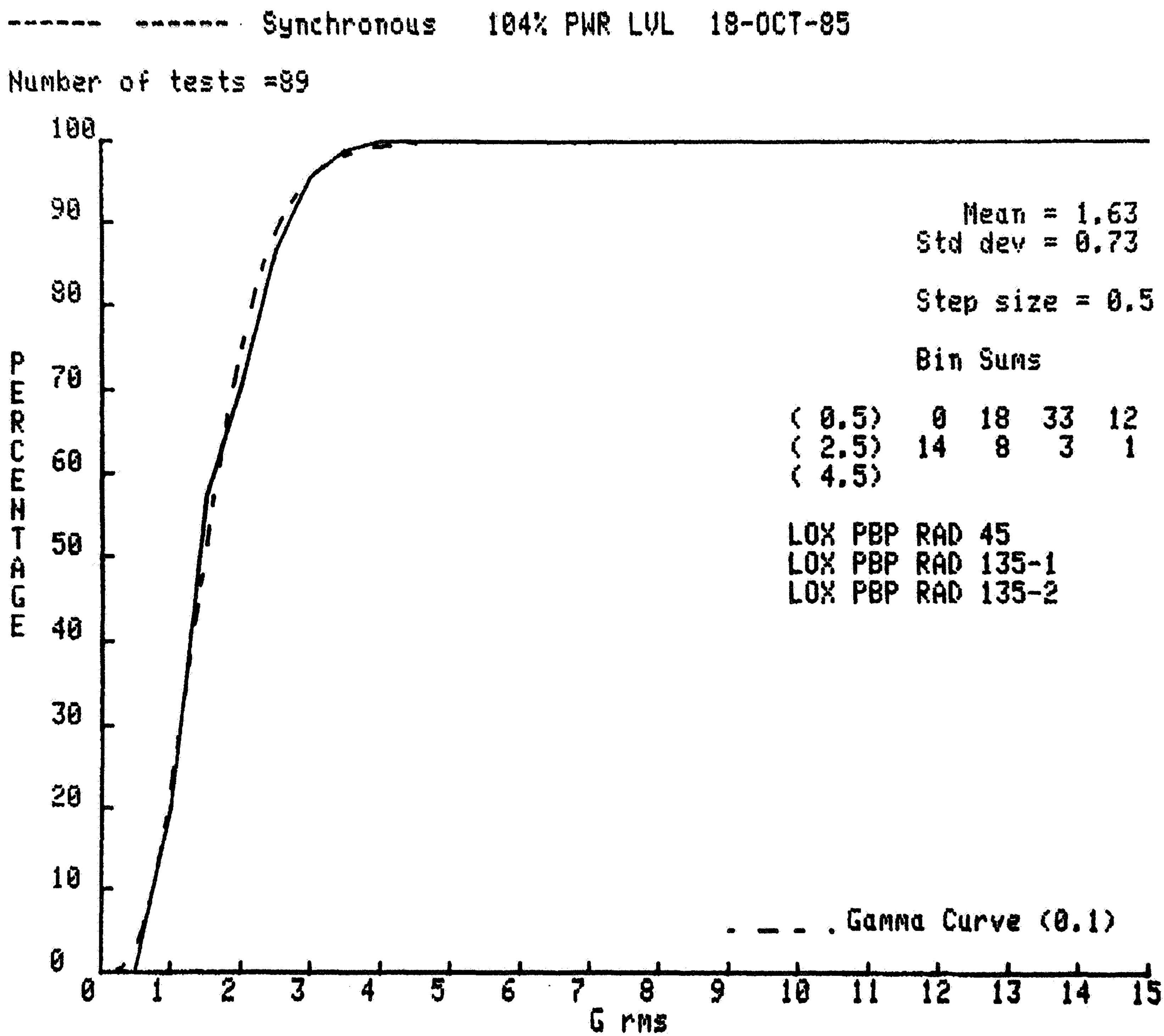
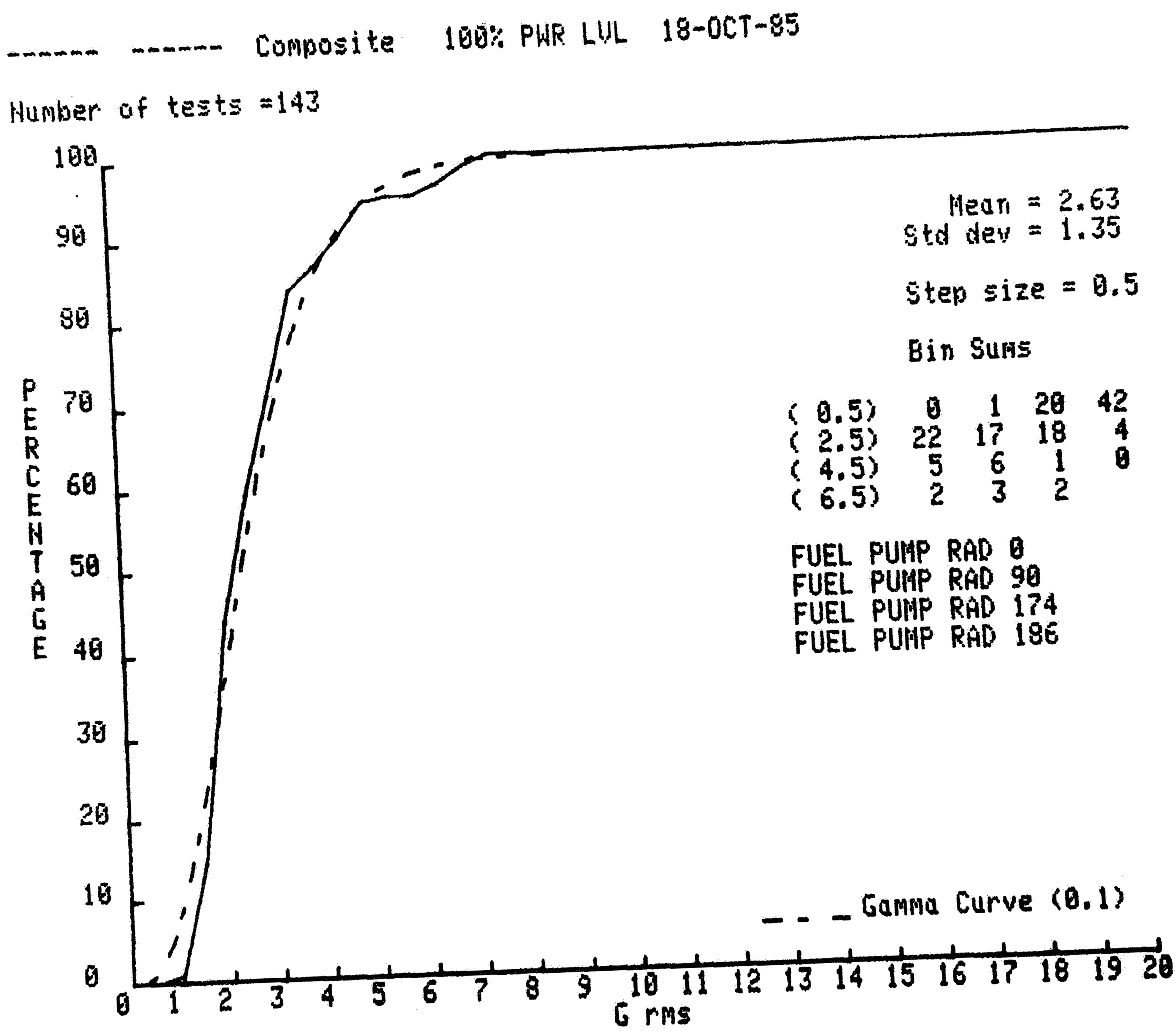
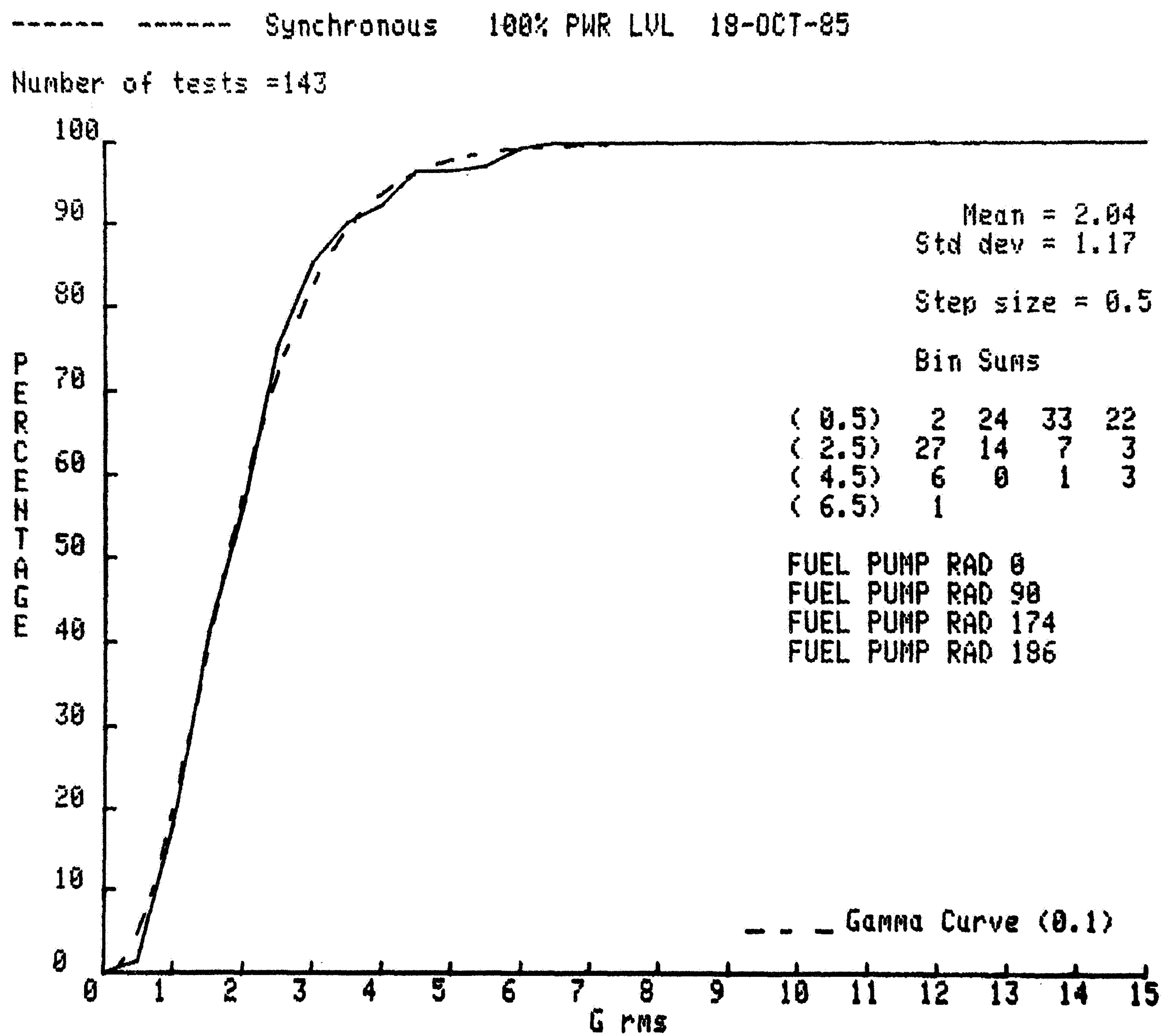

------ ------ Composite 104% PWR LVL 18-OCT-85
Number of tests =89
PERCENTAGE
0
10
20
30
40
50
60
70
80
90
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
G rms
Mean = 3.03
Std dev = 1.24
Step size = 0.5
Bin Sums
(0.5) 0 1 4 14
(2.5) 16 15 16 9
(4.5) 4 3 2 3
(6.5) 0 1 1
FUEL PUMP RAD 0
FUEL PUMP RAD 90
FUEL PUMP RAD 174
FUEL PUMP RAD 186
- - - Gamma Curve (0.1)

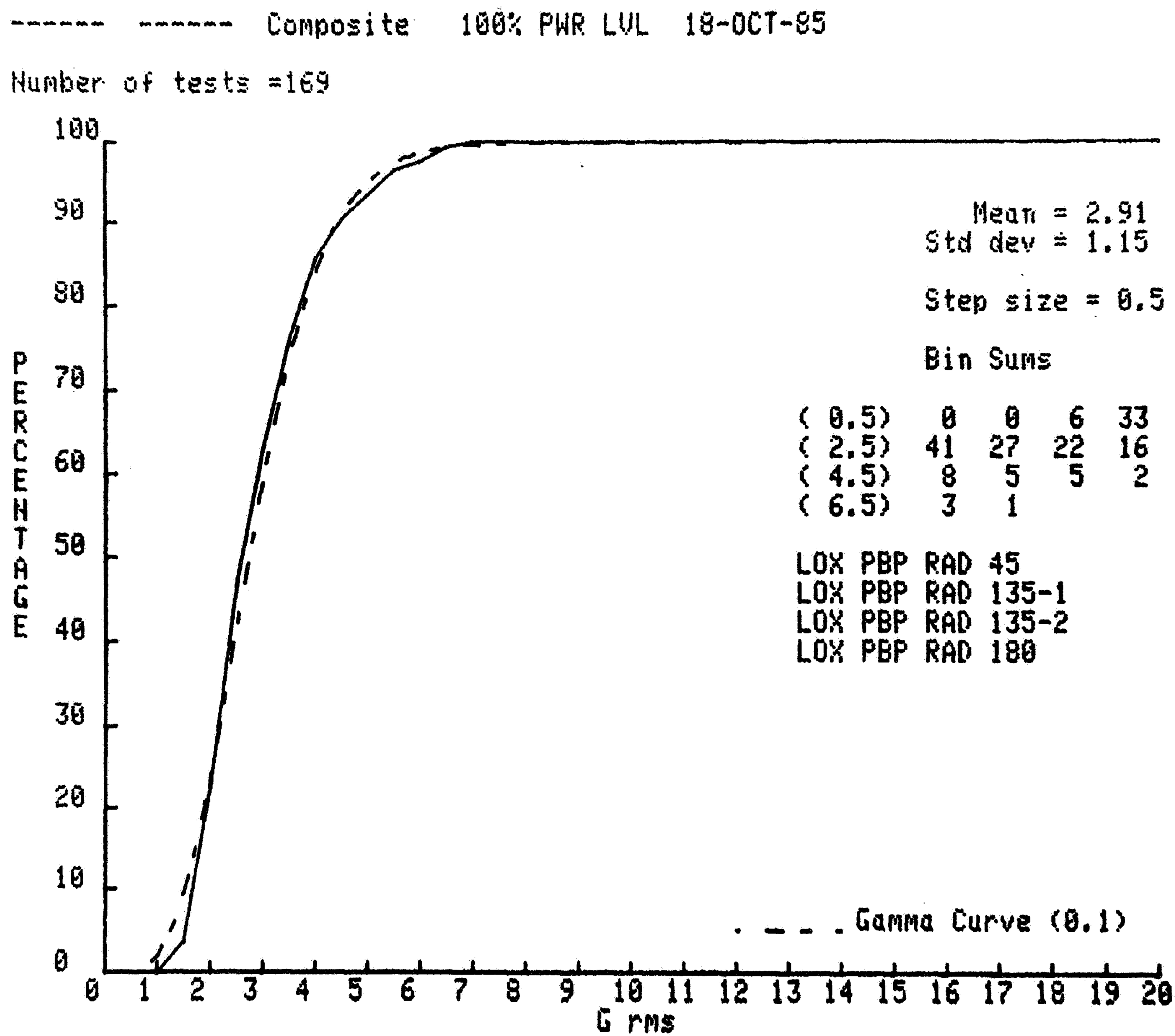

------ ------ Synchronous 104% PWR LVL 18-OCT-85
Number of tests =89
PERCENTAGE
0
10
20
30
40
50
60
70
80
90
100
G rms
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Mean = 2.50
Std dev = 1.09
Step size = 0.5
Bin Sums
(0.5) 0 6 10 18
(2.5) 14 13 13 8
(4.5) 2 3 2
FUEL PUMP RAD 0
FUEL PUMP RAD 90
FUEL PUMP RAD 174
FUEL PUMP RAD 186
_ _ _ Gamma Curve (0.1)

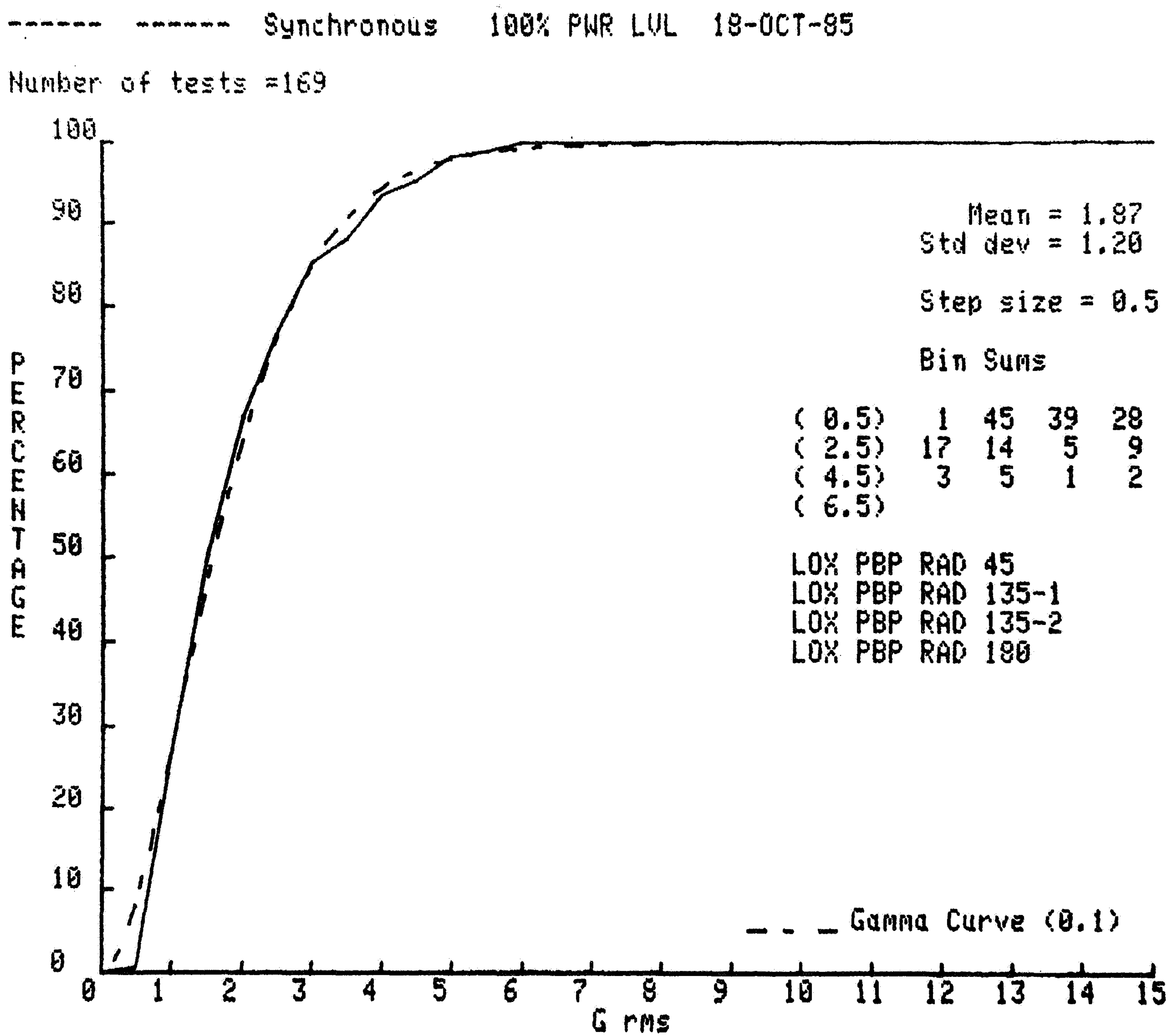

------ ------ Composite 104% PWR LVL 18-OCT-85
Number of tests =88
PERCENTAGE
0
10
20
30
40
50
60
70
80
90
100
Mean = 2.80
Std dev = 0.81
Step size = 0.5
Bin Sums
(0.5) 0 0 1 9
(2.5) 37 12 15 6
(4.5) 5 2 0 0
(6.5) 1
LOX PBP RAD 45
LOX PBP RAD 135-1
LOX PBP RAD 135-2
Gamma Curve (0.1)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
G rms


------ ------ Synchronous 104% PWR LVL 18-OCT-85
Number of tests =89
100
90
80
70
60
50
40
30
20
10
0
PERCENTAGE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
G rms
Mean = 1.63
Std dev = 0.73
Step size = 0.5
Bin Sums
(0.5) 0 18 33 12
(2.5) 14 8 3 1
(4.5)
LOX PBP RAD 45
LOX PBP RAD 135-1
LOX PBP RAD 135-2
Gamma Curve (0.1)


Composite 100% PWR LVL 18-OCT-85
Number of tests =143
PERCENTAGE
0
10
20
30
40
50
60
70
80
90
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
G rms
Mean = 2.63
Std dev = 1.35
Step size = 0.5
Bin Sums
(0.5) 0 1 20 42
(2.5) 22 17 18 4
(4.5) 5 6 1 0
(6.5) 2 3 2
FUEL PUMP RAD 0
FUEL PUMP RAD 90
FUEL PUMP RAD 174
FUEL PUMP RAD 186
Gamma Curve (0.1)


------ ------ Synchronous 100% PWR LVL 18-OCT-85
Number of tests =143
PERCENTAGE
0 10 20 30 40 50 60 70 80 90 100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
G rms
Mean = 2.04
Std dev = 1.17
Step size = 0.5
Bin Sums
(0.5) 2 24 33 22
(2.5) 27 14 7 3
(4.5) 6 0 1 3
(6.5) 1
FUEL PUMP RAD 0
FUEL PUMP RAD 90
FUEL PUMP RAD 174
FUEL PUMP RAD 186
Gamma Curve (0.1)


------- ------- Composite 100% PWR LVL 18-OCT-85
Number of tests =169
PERCENTAGE
0
10
20
30
40
50
60
70
80
90
100
G rms
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Mean = 2.91
Std dev = 1.15
Step size = 0.5
Bin Sums
(0.5) 0 0 6 33
(2.5) 41 27 22 16
(4.5) 8 5 5 2
(6.5) 3 1
LOX PBP RAD 45
LOX PBP RAD 135-1
LOX PBP RAD 135-2
LOX PBP RAD 180
Gamma Curve (0.1)


------ ------ Synchronous 100% PWR LVL 18-OCT-85
Number of tests =169
PERCENTAGE
100
90
80
70
60
50
40
30
20
10
0
Mean = 1.87
Std dev = 1.20
Step size = 0.5
Bin Sums
(0.5) 1 45 39 28
(2.5) 17 14 5 9
(4.5) 3 5 1 2
(6.5)
LOX PBP RAD 45
LOX PBP RAD 135-1
LOX PBP RAD 135-2
LOX PBP RAD 180
Gamma Curve (0.1)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
G rms

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HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2115	2016R3	2018R2	2022R2	9211R2	4102R1
TEST NUMBER	STS51IE1	STS51IE2	STS51IE3	STS51JE1	STS51JE2	STS51JE3
PWR LVL/SYNC FREQ	104%/473	104%/465	104%/478	104%/465	104%/475	104%/468
PUMP RAD (45)						(?)
Composite	2.2	2.7	2.3	2.1	2.4	2.0
Synchronous	0.9	0.6	0.6	0.8	1.5	0.4
PUMP RAD (135-1)					(noisy)	
Composite	3.0	2.3	3.1	2.2	6.1	2.5
Synchronous	2.3	1.4	1.7	1.5	2.2	1.3
PUMP RAD (135-2)						(noisy)
Composite	3.5	3.9	3.1	2.4	3.2	4.5
Synchronous	2.4	1.4	1.7	1.5	1.9	1.3
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	2121R1	4201R2	4003R1	5301	2120	2218R1
TEST NUMBER	STS51IE1	STS51IE2	STS51IE3	STS51JE1	STS51JE2	STS51JE3
PWR LVL/SYNC FREQ	104%/590	104%/593	104%/593	104%/593	104%/588	104%/593
PUMP RAD (0)						
Composite	4.1	1.9	6.0	1.9	1.8	
Synchronous	3.8	1.6	5.3	1.3	1.4	
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite	4.4	2.5	7.0	1.7	1.8	2.2
Synchronous	4.0	1.6	5.4	1.0	1.2	1.8
PUMP RAD (186)						
Composite	3.8	2.8	3.7	1.4	1.8	1.9
Synchronous	3.1	2.2	3.4	0.8	1.4	1.6
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

HPOPT DATA COMPARISON *=early co

PUMP SERIAL #	2115	2016R3	2019R2	2022R2	9211R2	4102R1
TEST NUMBER	STS51IE1	STS51IE2	STS51IE3	STS51JE1	STS51JE2	STS51JE3
PWR LVL/SYNC FREQ	100%/448	100%/448	100%/460	100%/453	100%/458	100%/480
PUMP RAD (45)						(?)
Composite	2.2	2.2	2.1	2.2	2.3	1.9
Synchronous	1.1	0.4	0.4	0.9	1.5	0.3
			ss=0.6	ss=0.5		
PUMP RAD (135-1)					(noisy)	
Composite	3.1	1.9	2.4	2.0	4.4	2.1
Synchronous	2.5	0.7	1.2	1.4	2.1	0.7
			ss=0.6	ss=0.6		
PUMP RAD (135-2)						(noisy)
Composite	3.5	2.7	2.4	2.3	2.5	4.0
Synchronous	2.7	0.7	1.2	1.2	1.7	0.9
			ss=0.6	ss=0.5		
PUMP RAD (180)						
Composite						
Synchronous						
PUMP RAD (225)						
Composite						
Synchronous						
TURB. RAD (45)						
Composite						
Synchronous						
TURB. RAD (90)						
Composite						
Synchronous						
TURB. RAD (135)						
Composite						
Synchronous						

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HPFPT DATA COMPARISON *=early co

PUMP SERIAL #	2121R1	4201R2	4003R1	5301	2120	2218R1
TEST NUMBER	STS51IE1	STS51IE2	STS51IE3	STS51JE1	STS51JE2	STS51JE3
PWR LVL/SYNC FREQ	100%/575	100%/575	100%/578	100%/578	100%/573	100%/578
PUMP RAD (0)						
Composite	2.9	1.6	3.4	2.5	1.5	
Synchronous	2.1	1.2	3.0	1.9	0.8	
PUMP RAD (90)						
Composite						
Synchronous						
PUMP RAD (174)						
Composite	3.1	1.7	6.6	1.7	1.6	1.5
Synchronous	2.0	1.3	4.2	1.2	1.0	1.1
PUMP RAD (186)						
Composite	3.2	1.7	2.7	1.5	1.5	1.7
Synchronous	2.0	1.3	2.4	0.8	1.0	1.3
TURB. RAD (90)						
Composite						
Synchronous						
TURBINE AXIAL						
Composite						
Synchronous						
TURB. RAD (180)						
Composite						
Synchronous						
PUMP RAD (125)						
Composite						
Synchronous						

APPENDIX D

WYLE LABORATORIES - RESEARCH STAFF
TECHNICAL MEMORANDUM 65058-02-TM

ANALYSIS OF THE SYNCHRONOUS VIBRATION LEVELS FROM "HIGH RUNNING MAIN IMPELLERS" ON THE SSME HIGH PRESSURE OXIDIZER TURBOPUMP

APPENDIX D

WYLE LABORATORIES - RESEARCH STAFF TECHNICAL MEMORANDUM 64058-02-TM

ANALYSIS OF THE SYNCHRONOUS VIBRATION LEVELS FROM "HIGH RUNNING MAIN IMPELLERS" ON THE SSME HIGH PRESSURE OXIDIZER TURBOPUMP

by

Wayne L. Swanson

An interim report of
work performed under contract NAS8-33508

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

FOREWORD

Wyle Laboratories' Scientific Services & Systems Group prepared this report for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration. The work was performed under contract NAS8-33508, entitled "Dynamic Analysis of SSME Vibration and Pressure Data." Technical assistance and encouragement were provided by Mr. W. C. Smith, MSFC/ED24. The special assistance of Mr. P. Lewallen, MSFC/ED24, is acknowledged for modifying the MSFC Diagnostic Data Base Program software to calculate a unique spatial average. The contribution of other members of ED24 and Wyle Laboratories Research Department is also acknowledged.

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1.0 INTRODUCTION AND CONCLUSIONS

The purpose of this report is threefold: 1) to document an investigation of higher than expected (number of occurrences and amplitude) synchronous vibration levels on the high pressure oxidizer turbopump (HPOTP), 2) to illustrate the value of basic fundamental statistical methods of data analysis, incorporated in the MSFC Diagnostic Data Base Program, and 3) to document a data list of tests where the HPOTP vibration data are not contaminated by high running main impellers, whirl, instrumentation malfunctions, etc. Both the HPOTP Preburner Pump (PBP) and Turbine (TURB) measurements were considered in the analysis, operating at 100%, 104% and 109% power levels.

The terminology "High Running Main Impellers" was applied, after the study was completed, to an investigation in the last quarter of 1982 and early 1983 of higher than expected (number and amplitude) synchronous vibration levels on the HPOTP. When the original study was performed the vibration data was hand plotted in a format similar to the plotting routines now available using the MSFC Diagnostic Data Base Program. Data in this reports documents a re-evaluation and update of the original effort with maximum utilization of the MSFC computer program for data sorting, analysis and plotting. Analysis included calculation of the mean, standard deviation, spatial average, cumulative distribution and probability density with the classical Gamma distribution plotted as an overlay. Elegant and/or sophisticated statistical techniques were not used or required in the analysis, since visual methods were adequate to show a distinct difference between data groups.

This report does not change the conclusions and results of the original study which indicated a strong correlation between six main impellers and the high synchronous vibration levels. The analysis does, however, illustrate the application of probability density estimates for detecting embedded measurement groups representing differing statistical (and likely physical) behavior. In addition, the statistical characterization of the vibration data provided herein represents nominal HPOTP operation for future reference.

2.0 TECHNICAL DISCUSSION

2.1 Diagnostic Data Base

Table I is a listing of the relevant vibration measurements stored in the MSFC Diagnostic Data Base Program. The listing includes the test number, date of test, engine serial number, HPFTP serial number, HPOTP serial number and the power level of which the vibration data was acquired. For this analysis the number of tests at each power level was:

407 tests @ 100%

155 tests @ 104%

234 tests @ 109%.

These tests resulted in the following synchronous vibration data sample for analysis at the HPOTP preburner pump and turbine measurement locations. Each measurement was treated as an individual data point and therefore the results represent the spatial average over the transducer locations.

Number of Data Samples	Power Level	Measurement Location
1299	100%	LOX PBP RAD 45, 135-1, 135-2, 180, 225
542	104%	
712	109%	
971	100%	LOX TURB RAD 45, 90, 135
348	104%	
546	109%	

Serial numbers of HPOTP's with the suspect main impellers discussed in Section 2.4 are highlighted and the tests marked with an "H". Also the tests that experienced whirl are marked with an "SS" and the power level noted in the remarks column. These tests were also deleted before calculation of the statistics for normal turbopump operation.

2.2 Vibration Measurement Location

The plane in which the preburner pump and turbine accelerometers are located is shown in Figure 1. All accelerometers were oriented to measure the vibration in the radial direction. In Figure 2 the major components of the HPOTP pump section are identified including the main impeller.

TABLE I. SSME HIGH PRESSURE OXIDIZER AND FUEL TURBOPUMP VIBRATION DATA IN MSFC DIAGNOSTIC DATA BASE

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A1-194	9/6/78	0005	9003R2	0105	X		
A1-237	05/02/79	2007	2006	2005	X		
A1-238	05/05/79	2007	2006	2005	X		
A1-239	05/10/79	2007	2006	2005	X		
A1-240	05/12/79	2007	2006	2005	X		
A1-244	6/12/79	2006	0106	0006	X		
A1-245	6/16/79	2006	0106	0006	X		
A1-254	08/27/79	0007	0007R2	2006	X		
A1-259	10/12/79	0008	2007	9006	X		
A1-260	10/18/79	0008	2007	9006	X		
A1-262	11/24/79	0008	2007R1	9006	X		
A1-267	02/02/80	0009	9007	2007	X		
A1-270	02/29/80	0009	9007R2	2007	X		
A1-271	03/05/80	0009	9007R2	2007	X		
A1-272	03/15/80	0009	9007R2	2007	X		
A1-273	03/22/80	0009	9007R2	2007	X		
A1-274	03/28/84	0009	9007R2	2007	X		
A1-275	04/08/80	0009	9007R2	2007	X		
A1-278	04/21/80	0009	9007R2	2007	X		
A1-279	04/25/80	0009	9007R2	2007	X		
A1-280	04/28/80	0009	9007R2	2007	X		
A1-282	6/16/80	2007	9006R1	$\boxed{0007R1}$	X		
A1-284	07/30/80	0010	0010	9106	X		
A1-286	08/29/80	0009	9107	9108	X		
A1-287	09/02/80	0009	9107	9108	X		
A1-289	09/18/80	0009	0010R1	0305R1	X		
A1-290	10/07/80	0009	0010R1	0009	X		
A1-291	10/10/80	0009	0010R1	0009		X	
A1-301	12/15/80	0009	9008R2	2206	X		
A1-303	1/19/81	0009	90201R2	9208	X		
A1-304	1/21/81	0009	90201R2	9208	X		

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A1-305	1/23/81	0009	90201R2	9208	X		
A1-306	1/26/81	0009	90201R2	9208	X		
A1-309	2/28/81	0006	0007R5	2107	X		
A1-310	3/3/81	0006	0007R5	2107	X		
A1-311	3/5/81	0006	0007R5	2107	X		
A1-312	3/14/81	0006	0007R5	2107	X		
A1-313	3/18/81	0006	0007R5	2107	X		
A1-314	3/20/81	0006	0007R5	2107	X		
A1-315	3/26/81	0006	0007R5	2107	X		
A1-316	4/14/81	0006	0007R5	2602	X		
A1-317	4/20/81	0006	0007R5	2602	X		
A1-319	4/23/81	0006	0007R5	2602	X		
A1-321	5/13/81	2108	0210R1	2306	X		
A1-322	5/21/81	2108	0210R1	2306	X	X	X
A1-323	5/26/81	2108	0210R1	2306	X	X	X
A1-324	5/28/81	2108	0210R1	2306	X		X
A1-325	5/30/81	2108	0210R1	2306	X		X
A1-326	6/6/81	2108	2007R4	2306	X		
A1-327	6//11/81	2108	0210R2	2306	X		X
A1-328	6/16/81	2108	2010	2306	X		X
A1-329	06/23/81	2108	2010	2306	X		X
A1-330	7/10/81	2108	2010	2306	X		X
A1-331	7/15/81	2108	2010	2306			X
A1-333	8/11/81	0008	2007R4	9303R2	X		
A1-334	8/14/81	0008	2007R4	9303R2	X		
A1-335	8/17/81	0008	2007R4	9303R2	X		
A1-336	8/19/81	0008	2007R4	9303R2	X		
A1-338	10/9/81	0107	0210R4	0209	X		
A1-339	10/13/81	0107	0210R4	0209	X		
A1-340	10/15/81	0107	0210R4	0209	X		X
A1-341	10/30/81	0107	2308	0209	X		X

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
	A1-342	11/5/81	0107	2308	0209			X	
	A1-343	11/8/81	0107	2308	0209			X	
H	A1-344	11/14/81	0107	2110	2109			X	
H	A1-345	11/18/81	0107	2110	2109			X	
H	A1-346	11/19/81	0107	2110	2109			X	
H	A1-347	11/30/81	0107	2110R2	2109	X			
H	A1-348	12/2/81	0107	2110R2	2109			X	
H	A1-349	12/4/81	0107	2110R2	2109			X	
	A1-350	12/16/81	0107	9009	2105R1	X			
	A1-351	12/28/81	0107	2210	0209R1			X	
	A1-352	12/30/81	0107	2210	0209R1			X	
	A1-353	1/14/82	0107	2111	2011R1			X	
	A1-354	1/18/82	0107	2111	2011R1			X	
	A1-355	1/20/82	0107	2111	2011R1			X	
SS H	A1-357	2/1/82	0107	2111R1	2108			X	Whirl 109%
H	A1-358	2/8/82	0107	2111R2	2108			X	
	A1-360	03/10/82	2013	9109	9308	X			
	A1-361	03/22/82	2013	2211	2210			X	
	A1-362	3/27/82	2013	2211R1	2210			X	
SS	A1-363	03/30/82	2013	2211	2210	X		X	Whirl 109%
	A1-364	4/7/82	2013	2211R1	2014			X	
H	A1-366	5/19/82	2014	2113	2211	X			
	A1-367	05/25/82	2014	2113	2113			X	
	A1-368	6/3/82	2014	2212	2113			X	
	A1-369	6/5/82	2014	2212	2113			X	
	A1-370	6/7/82	2014	2212	2113			X	
	A1-371	06/15/82	2014	2113R1	2113			X	
	A1-372	06/17/82	2014	2113R1	2113			X	
	A1-373	6/22/82	2014	2113R1	9408	X			
H	A1-374	06/30/82	2014	2113R1	2212			X	
H	A1-375	07/03/82	2014	2113R1	2212	X			

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
H	A1-376	7/10/82	2014	9006R2	2212	X			
H	A1-377	7/14/82	2014	9006R2	2212	X			
H	A1-379	7/25/82	2014	2113R2	2212	X		X	
H	A1-380	7/27/82	2014	2113R2	2212	X		X	
H	A1-381	07/30/82	2014	2113R2	2212			X	
H	A1-382	08/02/82	2014	2113R2	2212	X			
H	A1-383	08/15/82	2014	2113R3	0007R2	X			
	A1-384	08/24/82	2014	2113R3	9508	X		X	
	A1-385	08/27/82	2014	2113R3	9508			X	
H	A1-389	9/25/82	2011	2214R1	0110R1	X	X		
	A1-390	10/04/82	2011	2214R1	9010	X	X	X	
	A1-391	10/07/82	2011	2214R1	9010	X	X		
H	A1-393	10/21/82	2012	2213	2312	X			
	A1-394	10/26/82	2012	2213	2410	X	X	X	
	A1-395	10/30/82	2012	2213	2410	X		X	
H	A1-397	12/07/82	2014	9409	2311	X			
H	A1-398	12/14/82	2014	9409	2311	X		X	
H	A1-399	12/18/82	2014	9409	2311	X		X	
SS H	A1-400	12/23/82	2014	9409	2311	X		X	Whirl 109%
H	A1-401	1/5/83	2014	9409	9111			X	
H	A1-402	1/8/83	2014	9409	9111			X	
H	A1-403	1/22/83	2014	9111	2311R1	X			
H	A1-404	1/28/83	2014	9111	2311R1	X		X	
H	A1-405	02/04/83	2014	9509	2311R1	X		X	
	A1-406	02/17/83	2014	9509	9608	X	X		
	A1-407	3/13/83	2014	9509	2410	X	X		
	A1-408	4/6/83	2014	9509	2410R1	X	X		
	A1-409	04/20/83	2014	9509	2410R1	X	X		
	A1-410	4/23/83	2014	9509	2410R1	X	X		
	A1-413	05/25/83	2018	0209	9211	X	X		
	A1-414	6/6/83	2018	2314R1	9211	X	X		

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
	A1-416	7/11/83	2010	0209R1	2410R1	X	X		
	A1-417	7/15/83	2010	0209R1	2410R1	X	X		
	A1-418	7/20/83	2010	0209R1	2410R1	X	X		
	A1-419	8/12/83	2010	2414	2410R2	X	X		
	A1-420	08/30/83	2010	2414	2410R2	X	X		
	A1-421	09/25/83	2010	2414R1	2410R2	X	X		
	A1-422	9/29/83	2010	2414R1	2410R2	X			
	A1-423	10/1/83	2010	2414R1	2410R2	X			
	A1-424	10/13/83	2010	2109	0310	X	X		
	A1-425	10/17/83	2010	2109	0310	X	X		
	A1-426	10/24/83	2010	2109	0310	X			
	A1-427	11/2/83	2010	5101R1	0310	X	X		
	A1-428	11/18/83	2010	2410	0310	X	X		
	A1-429	11/23/83	2010	2410	0310	X	X		
	A1-430	12/7/83	2017	2415	9010R1	X	X		
H	A1-432	1/4/84	0108	0506	$\boxed{2209R1}$	X	X		
	A1-433	01/21/84	0108	0107	2512	X	X	X	
	A1-434	01/24/84	0108	0107	2512	X		X	
	A1-435	2/8/84	0108	0107	2512	X		X	
	A1-436	2/14/84	0108	0606	2512	X		X	
	A1-437	3/22/84	2019	9210	2019	X	X		
	A1-438	3/27/84	2019	9210	2019	X	X		
	A1-439	04/06/84	2019	2020	2022	X	X		
	A1-440	4/11/84	2019	4002	2022	X	X		
H	A1-442	5/8/84	0207	2109R1	$\boxed{0207}$	X	X		
H	A1-443	5/14/84	0207	2109R1	$\boxed{0207}$	X	X	X	
SS H	A1-444	5/18/84	0207	2109R1	$\boxed{0207}$	X	X	X	Whirl 104%
	A1-445	6/9/84	0207	2109R1	2308R1	X		X	
	A1-446	06/15/84	0207	2109R1	2308R1	X	X		
	A1-447	6/27/84	0207	2608	2308R1	X		X	
	A1-448	7/10/84	0207	2608	2308R1	X		X	

TABLE 1. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A1-449	7/14/84	0207	2608	2308R1	X		X
A1-450	7/26/84	0207	0309R1	2308R1	X		X
A1-451	8/9/84	0207	0309R2	2308R1	X		
A1-452	8/21/84	0207	90701R1	2606R2	X		X
A1-453	08/31/84	0207	90701R1	2606R2	X	X	X
A1-454	09/12/84	0207	90701R1	2606R2	X		X
A1-455	09/21/84	0207	90701R2	2606R3	X		X
A1-456	9/25/84	0207	90701R2	2606R3	X		X
A1-457	09/29/84	0207	90701R2	2606R3	X		X
A1-458	10/05/84	0207	90701R2	2606R3	X		X
A1-459	10/26/84	0207	0309R3	2606R3	X		X
A1-460	11/12/84	0207	0309R3	9505	X		X
A1-461	12/28/84	0207	2209	9505R1	X		X
A1-462	01/05/85	0207	2209R1	9505R1	X		X
A1-463	01/14/85	0207	2209R1	9505R1	X		X
A1-464	1/17/85	0207	2209R1	9505R1	X		X
A1-465	1/19/85	0207	2209R1	9505R1	X		X
A1-466	1/24/85	0207	2209R1	9505R1	X		X
A1-467	1/30/85	0207	2209R1	9505R1	X		X
A1-468	02/04/85	0207	2209R2	9505R1	X		X
A1-470	2/25/85	2105	4004	2217	X	X	X
A1-471	02/27/85	2105	4004	2217	X		X
A1-472	03/04/85	2105	4004R1	2217	X	X	
A1-473	03/06/85	2105	4004R1	2217	X		X
A1-474	3/22/85	2105	4004R1	9808	X		X
A1-475	4/17/85	2105	4004R2	9808	X	X	
A1-476	5/21/85	2105	5102R1	9505R2	X		X
A1-477	05/24/85	2105	5102R1	9505R2	X	X	X
A1-478	06/01/85	2105	5102R1	9505R2	X		X
A1-479	6/5/85	2105	5102R1	9505R2	X		X
A1-480	6/7/85	2105	5102R1	9505R2	X		X

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A1-481	6/10/85	2105	5102R1	9505R2	X	X	
A1-482	7/9/85	2105	5102R1	4004	X	X	
A1-483	7/13/85	2105	5102R1	4004	X	X	
A1-484	7/19/85	2105	5102R1	4004	X		X
A1-485	7/24/85	2105	4104	4004	X		X
A1-486	07/30/85	2105	5102R1	4004	X	X	
A1-487	7/4/85	2105	5102R1	4004	X	X	X
A1-488	08/07/85	2105	5102R1	4004R1	X		
A1-489	8/12/85	2105	0307	4004	X	X	
A1-490	8/31/85	2105	0307	4004R1	X		X
A1-491	9/7/85	2105	0307	4004R1	X		X
A1-492	09/19/85	2105	0307	4004R1	X		X
A1-493	9/24/85	2105	0307R1	4004R1	X	X	X
A1-495	10/22/85	2026	2614	2504	X	X	
A2-145	12/08/78	2002	2103	0205	X		
A2-193	4/19/80	2004	2304R1	9008	X		X
A2-195	6/20/80	2004	2404	9104R1	X		
A2-200	9/13/80	2008	9008	0106R3	X		
A2-201	9/16/80	2008	9008	0106R3	X	X	
A2-202	9/23/80	2008	9008	0106R3	X		
A2-204	10/13/80	0006	0007R5	2107	X		
A2-206	10/30/80	2008	9009R1	0106R4	X		
A2-212	12/10/80	2008	0110	0009R2		X	
A2-218	2/3/81	2009	2009	0010	X		
A2-219	2/9/81	2009	2009	0010	X		
A2-220	3/7/81	0008	90301	0109	X		
A2-221	3/10/81	0008	90301	0109	X		
A2-223	3/17/81	0008	90301	0109			X
A2-224	3/24/81	0008	0208R1	0109			X
A2-228	4/21/81	0204	2108	0405	X		
A2-229	4/24/81	0204	2108	0405	X		

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A2-230	4/27/81	0204	2108	0405			X
A2-231	5/5/81	0204	2108R1	0405			X
A2-232	5/7/81	0204	2108R1	0405			X
A2-233	5/9/81	0204	2108R1	0405			X
A2-234	5/14/81	0204	2108R1	0405			X
A2-235	5/19/81	0204	2108R1	0405			X
A2-236	5/23/81	0204	2108R1	0405			X
A2-237	6/5/81	0204	9108	0010R1			X
A2-238	6/9/81	0204	9108	0010R1			X
A2-239	6/19/81	0204	9108	2602R1			X
A2-240	6/22/81	0204	9108	2602R1	X		
A2-241	6/24/81	0204	9108	2602R1			X
A2-242	07/02/81	0204	9108	0108			X
A2-243	07/08/81	0204	9108	0108			X
A2-244	07/14/81	0204	9108	0108	X		
A2-245	08/12/81	0204	0210R3	2009			X
A2-246	08/22/81	0204	0210R3	0203			X
A2-247	08/31/81	0204	9108	0203			X
A2-248	09/14/81	0204	9108	9204			X
A2-251	12/11/81	2010	2012	2010	X		
A2-252	12/14/81	2010	2012	2010			X
A2-253	12/18/81	2010	2012	2010			X
A2-254	12/21/81	2010	2012	2010			X
A2-255	01/02/82	2010	2012R1	2406	X		X
A2-256	01/05/82	2010	2012R1	2406	X		X
A2-257	01/07/82	2010	2012R1	2406	X		X
A2-258	01/16/82	2010	2012R2	2406	X		
A2-259	01/18/82	2010	2012R2	2406			X
A2-261	1/29/82	2010	9009R1	2110	X		X
A2-263	2/6/82	2010	9009R1	2110	X		
A2-264	02/09/82	2010	9009R1	2110	X		

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
H	A2-265	02/19/82	2010	2112	2108R1	X			
SS H	A2-266	02/22/82	2010	2112	2108R1			X	Whirl 109%
	A2-267	03/08/82	2010	2112R1	2013			X	
H	A2-268	3/16/82	2010	2112R1	2111	X		X	
SS H	A2-270	03/29/82	2010	2112R2	2111			X	Whirl 109%
	A2-271	04/30/82	2010	0306R2	2310	X			
	A2-272	5/5/82	2010	2112R4	2310			X	
	A2-273	5/8/82	2010	2115	2310	X		X	
	A2-274	05/11/82	2010	2115	2310	X		X	
	A2-276	5/29/82	2010	2115R1	2310R1			X	
	A2-277	6/6/82	2010	2114	0110			X	
	A2-279	6/20/82	2010	9208R2	2108R2			X	
	A2-283	7/4/82	2010	9208R2	2108R2			X	
	A2-284	7/9/82	2010	2310R1	2108R2			X	
	A2-285	07/13/82	2010	9208R3	2108R2	X			
	A2-286	07/19/82	2010	9209	2209			X	
	A2-288	07/27/82	2010	2214	2209			X	
	A2-289	08/01/82	2010	9010	2209	X		X	
	A2-290	8/5/82	2010	9309	2209			X	
	A2-291	8/7/82	2010	9309	2209			X	
	A2-292	08/09/82	2010	9309	2209	X		X	
	A2-294	09/10/82	2012	2214R1	9010	X	X		
	A2-296	09/25/82	2015	2215R1	2015	X	X		
	A2-297	9/30/82	2015	2215R1	2015			X	
	A2-298	10/06/82	2015	9010R2	2015	X	X	X	
	A2-299	10/8/82	2015	9010R2	2015			X	
	A2-302	11/15/82	2016	9011	2016	X	X		
	A2-303	12/5/82	2016	9110	2410	X	X	X	
	A2-304	12/7/82	2016	9110	2410			X	
	A2-306	01/13/83	2017	2016R1	0210R1	X			
	A2-307	2/15/83	2017	2016R1	9010	X	X		

TABLE I. - (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
H	A2-309	4/14/83	2011	2017	2208	X			
H	A2-310	4/18/83	2011	2017	2208	X	X		
	A2-311	4/27/83	2011	2017R1	2018	X	X		
	A2-313	6/9/83	2019	9210	2019	X	X		
	A2-314	6/20/83	2019	9210	2019	X	X		
	A2-318	10/15/83	2109	5101	2020	X	X		
	A2-319	10/18/83	2109	5101	2020	X	X		
SS H	A2-322	11/11/83	2020	2018	0107	X	X		Whirl 104%
	A2-323	11/19/83	2020	2018	2021	X	X		
	A2-325	12/5/83	2021	2109	4001	X	X		
	A2-326	12/10/83	2021	2109	4001	X	X		
	A2-327	1/10/84	2010	2410	4002	X			
SS	A2-328	1/15/84	2010	2410	4002	X	X		Whirl 104%
	A2-329	01/25/84	2010	2410	9110	X	X		
	A2-331	2/13/84	2010	2514	0310	X	X		
	A2-332	3/13/84	2010	9211	0310	X	X		
	A2-333	03/21/84	2010	9211	0310	X	X		
	A2-335	4/12/84	2022	4001	2015R1	X	X		
	A2-336	05/10/84	2022	2020R1	2022	X	X		
	A2-337	5/22/84	2022	2020R1	2022	X	X		
	A2-339	06/13/84	2023	2021	2019R1	X	X		
	A2-340	06/21/84	2023	2515	2019R1	X	X		
	A2-341	06/30/84	2023	2515	2019R1	X	X		
	A2-343	7/21/84	2014	9310	2016R1	X	X		
SS	A2-344	8/7/84	2014	9311	2117	X	X		Whirl 104%
	A2-345	8/12/84	2014	4102	2117	X	X		
	A2-346	8/20/84	2014	2313	2117	X	X		
	A2-347	9/13/84	2014	2118	2115	X	X		
	A2-348	09/28/84	2014	2118	2016R2	X	X		
	A2-349	10/10/84	2014	9310R1	2018R1	X	X		
	A2-350	10/16/84	2014	2216	2018R1	X	X		

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
	A2-351	10/24/84	2014	4202	2022R1	X	X		
	A2-352	11/02/84	2014	4003	4102	X	X		
	A2-354	12/01/84	2014	2121	2016R3	X	X		
SS	A2-356	02/11/85	2015	4101	0310R2	X	X		Whirl 104%
	A2-357	02/19/85	2015	2413	4003	X	X		
	A2-358	3/5/85	2014	5301	4003	X	X		
	A2-359	03/13/85	2014	9410	4003	X	X		
	A2-360	3/16/85	2014	2120	4003	X	X		
	A2-361	3/27/85	2014	2218	9211R1	X	X		
	A2-363	4/25/85	2024	4201	2020R2	X	X		
	A2-364	5/3/85	2024	4202	2020R2	X	X		
	A2-365	5/13/85	2024	2218R1	4003R1	X	X		
	A2-366	6/17/85	2024	2413R1	2504	X	X		
	A2-367	6/29/85	2024	2413R1	2018R2	X	X		
	A2-368	7/2/85	2024	2413R1	2018R2	X			
	A2-369	07/17/85	2024	9510	2020R3	X	X		
	A2-371	08/03/85	2116	4104	2317	X	X	X	
	A2-372	8/985	2116	4104	2317	X		X	
	A2-373	8/13/85	2116	4104	2317	X	X		
	A2-374	8/17/85	2116	4104	2317	X	X		
H	A2-375	9/7/85	2116	4104	$\boxed{0307}$	X	X	X	
H	A2-376	9/13/85	2116	4104	$\boxed{0307}$	X	X	X	
	A2-377	9/17/85	2116	4104	2317R1	X		X	
	A2-378	9/20/85	2116	4104	2317R1	X		X	
	A2-379	9/25/85	2116	4104	2317R1	X			
	A2-380	10/7/85	2116	0409	9808R1	X		X	
	A2-381	10/14/85	2116	0409	9808R1	X		X	
	A2-382	10/19/85	2116	0409R1	9808R1	X			
	A2-383	10/26/85	2116	5301R1	9110R1	X	X		
	A2-384	11/05/85	2116	2117	4001R2	X	X		
	A3-074	4/5/80	0007	0306	2502	X			

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A3-075	4/12/80	0007	0404R1	2502	X		
A3-076	4/14/80	0007	0404R1	2502	X		
A3-077	4/21/80	0007	2106R5	2502	X		
A3-078	4/30/80	0007	0208	9303R1	X		
A3-079	5/7/80	0007	0208	0008	X		
A3-080	5/15/80	0007	0009	2106R1	X		
A3-081	5/21/80	0007	2106R5	2106R1	X		
A3-082	6/5/80	0007	2106R5	0106R1	X		
A3-083	6/9/80	0007	2106R5	0106R1	X		
A3-084	6/11/80	0007	2106R5	0106R1	X		
A3-085	6/19/80	0007	9205	0106R1	X		
A3-086	6/23/80	0007	9205	0106R1	X		
A3-087	7/3/80	0007	9205	2304	X		
A3-088	7/15/80	0007	0404	0106R1	X		
A3-089	7/29/80	0007	0007R4	0106R1	X		
A3-090	8/16/80	0007	9205R1	9104R3	X		
A3-091	8/20/80	0007	9205R1	9104R3	X		
A3-092	9/3/80	0007	9201	9104R3	X		
A3-093	9/9/80	0007	90201R1	9104R3	X		
A3-094	9/20/80	0007	90201R1	9104R3	X		
A3-095	9/27/80	0007	90201R1	9104R3	X		
A3-096	9/30/80	0007	90201R1	9104R3	X		
A3-097	10/2/80	0007	90201R1	9104R3	X		
A3-098	10/4/80	0007	90201R1	9104R3	X		
A3-099	10/7/80	0007	90201R1	9104R3	X		
A3-100	10/9/80	0007	90201R1	9104R3	X		
A3-101	10/11/80	0007	90201R1	9104R3	X		
A3-102	10/20/80	0007	9205R2	2404	X		
A3-103	11/3/80	0007	90201R1	9305	X		
A3-104	11/7/80	0007	90201R1	9305	X		
A3-105	11/8/80	0007	90201R1	9305	X		

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
A3-106	11/11/80	0007	90201R1	9305	X		
A3-108	11/15/80	0007	90201R1	9305	X		
A3-109	11/18/80	0007	90201R1	9305	X		
A3-110	11/25/80	0007	90201R1	9104R3	X		
A3-111	12/1/80	0007	90201R1	9104R3	X		
A3-112	12/6/80	0007	90201R1	9104R3	X		
A3-113	12/16/80	0007	9305	0106R5	X		
A3-114	12/18/80	0007	9305	0106R5	X		
A3-115	12/26/80	0007	9305	0106R5	X		
A3-116	1/7/81	0007	9305	0106R6	X		
A3-117	1/9/81	0007	9305	0106R6	X		
A3-118	1/22/81	0007	9305	0106R7	X		
A3-119	1/28/81	0007	0110R1	0106R7	X		
A3-120	2/7/81	0007	0110R1	0106R7	X		
A3-121	2/9/81	0007	0110R1	0106R7	X		
A3-123	2/25/81	0110	9008R3	9009R1	X		
A3-124	3/2/81	0110	9008R3	9009R1	X		
A3-125	3/11/81	0110	9008R3	0106R8	X	X	X
A3-126	3/14/81	0110	9008R3	0106R8			X
A3-127	3/24/81	0110	9008R3	2602	X		
A3-128	3/26/81	0110	9008R3	2602	X		
A3-129	3/28/81	0110	9008R3	2602	X		
A3-130	3/31/81	0110	9008R3	2602	X		
A3-131	4/13/81	0110	9008R3	9208R1			X
A3-132	4/17/81	0110	9008R3	9208R1			X
A3-133	4/27/81	0110	9008R3	0106R8			X
A3-134	5/7/81	0110	2206	0106R8			X
A3-135	5/9/81	0110	2206	0106R8			X
A3-136	5/12/81	0110	2206	0106R8			X
A3-138	5/19/81	0110	2206	0106R8			X
A3-139	5/26/81	0110	2206	0106R8			X

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
	A3-140	06/20/81	0110	2206	0405R1			X	
	A3-141	06/27/81	0110	2206	0405R1			X	
	A3-142	06/30/81	0110	2206	0405R1			X	
	A3-143	08/06/81	0110	2010R2	2602R2			X	
	A3-144	08/10/81	0110	2010R2	2602R2			X	
	A3-145	08/14/81	0110	2011	2602R2			X	
	A3-146	08/18/81	0110	2206	2602R2	X			
	A3-147	8/24/81	0110	2206	2602R2			X	
	A3-148	9/2/81	0110	2206	2602R2			X	
	A3-150	11/17/81	0110F	2308R1	0303	X		X	
	A3-152	12/10/81	0110F	2301	0303			X	
SS	A3-153	12/14/81	0110F	2301	0303			X	Whirl 109%
	A3-154	12/29/81	0110F	9009	2602R3			X	
	A3-156	1/11/82	0110F	9009	2602R3			X	
	A3-157	1/13/82	0110F	9009	2602R3			X	
	A3-158	1/15/82	0110F	9009	2602R3			X	
	A3-161	03/15/82	0107	2210R1	2406			X	
	A3-162	03/22/82	0107	2210R1	2406	X			
	A3-164	04/01/82	0107	2210R1	2406			X	
	A3-165	04/21/82	0107	2210R2	0309R1			X	
	A3-166	04/29/82	0107	9208	0309R1			X	
	A3-167	5/2/82	0107	9208	0309R1			X	
	A3-168	05/15/82	0107	9208R1	0309R1			X	
H	A3-170	7/29/82	2208	9208R3	2108R2	X			
H	A3-171	8/4/82	2208	9307	2108R2			X	
H	A3-172	8/7/82	2208	9307	2108R2			X	
SS H	A3-173	8/18/82	2208	9307	2212R1	X		X	Whirl 109%
	A3-174	08/25/82	2208	9307R1	2213			X	
	A3-177	11/02/82	2308	90401	2209R1	X	X	X	
	A3-178	11/07/82	2308	2315	2209R1	X	X	X	
	A3-181	11/24/82	2308	2016R1	2209R1	X	X	X	

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109	
SS	A3-182	12/01/82	2308	2312	2209R1	X		X	Whirl 109%
H	A3-183	12/08/82	2308	2312	0210	X	X	X	
	A3-184	12/16/82	2308	2312	2410	X		X	
	A3-185	01/05/83	2308	2312R1	2410	X			
	A3-186	01/10/83	2308	2312R1	2410	X		X	
	A3-187	1/15/83	2308	90501	2410	X		X	
	A3-188	1/19/83	2308	90501	2410	X		X	
H	A3-190	2/4/83	2308	90501	2412	X	X	X	
H	A3-191	2/12/83	2308	90501	9111R1	X		X	
H	A3-192	03/02/83	2308	90501	0210R2	X	X		
H	A3-193	3/23/83	2308	2017	2412	X	X		
H	A3-194	4/14/83	2308	2116	2412	X	X		
H	A3-195	4/23/83	2308	9211	2412	X	X		
H	A3-196	5/3/83	2308	2009	2412	X	X		
H	A3-197	5/16/83	2308	2412	2412	X	X		
H	A3-198	5/23/83	2308	2412	2412	X	X		
H	A3-199	5/28/83	2308	2314	2412	X	X		
H	A3-200	6/4/83	2308	2116R1	2412	X	X		
H	A3-201	6/9/83	2308	2116R1	2412	X	X		
H	A3-203	6/25/83	2308	2116R2	2412	X	X		
H	A3-204	6/30/83	2308	2512	2412	X	X		
H	A3-205	7/6/83	2308	2512	2412	X	X		
H	A3-206	7/11/83	2308	2414	2412	X	X		
H	A3-207	7/21/83	2308	2018	2412	X	X		
H	A3-208	8/2/83	2308	0406	2208	X	X		
H	A3-209	08/08/83	2308	0406	2208	X	X		
	A3-210	08/19/83	2308	0406	2309	X			
	A3-211	08/24/83	2308	0406	2309	X	X	X	
	A3-212	08/30/83	2308	0406	2309	X	X	X	
	A3-213	9/10/83	2308	0406	4001	X	X		
	A3-214	9/22/83	2308	0406	2309R1	X	X	X	

TABLE 1: (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
	A3-215	9/28/83	2308	0406	2309R1	X	X	X
H	A3-216	10/5/83	2308	0406	$\boxed{2208}$	X	X	
H	A3-217	10/11/83	2308	0406	$\boxed{2208}$	X		
H	A3-218	10/18/83	2308	0406	$\boxed{2208}$	X	X	
H	A3-219	10/24/83	2308	90601	$\boxed{2208}$	X	X	
	A3-220	11/1/83	2308	90601	2506	X		
	A3-221	11/10/83	2308	2410	2512	X	X	
	A3-222	11/15/83	2308	90601	2512	X	X	
	A3-224	12/10/83	2308	90601	2409	X		
	A3-225	12,15,83	2308	90601	2409	X	X	X
	A3-226	12/21/83	2308	90601	2409	X	X	X
	A3-227	12/28/83	2308	90601	2409	X	X	X
	A3-228	01/09/84	2308	90601R1	9708	X		
	A3-229	1/13/84	2308	90601R1	9708	X	X	X
	A3-230	1/19/84	2308	90601R1	9708	X	X	X
	A3-231	01/30/84	2308	90601R1	2409R1	X	X	X
	A3-232	2/6/84	2308	90601R1	2409R1	X	X	X
	A3-233	4/6/84	2308	2109R1	9708R1	X	X	X
	A3-234	4/19/84	2308	2508	2606	X		X
	A3-235	05/19/84	2308	0309	2409R2	X		X
	A3-236	06/15/84	2308	0207	2606R1	X	X	X
	A3-237	06/20/84	2308	0207	2606R1	X	X	X
	A3-238	06/26/84	2308	0207	2606R1	X		X
	A3-239	6/30/84	2308	0207	2606R1	X		X
	A3-240	07/09/84	2308	0207	2606R1	X		X
	A3-241	07/18/84	2308	0309R1	9708R1	X		X
	A3-242	7/26/84	2308	2608R1	9708R2	X		X
	A3-243	8/7/84	2308	2608R1	9708R2	X		X
	A3-244	08/15/84	2308	2608R2	9708R2	X		X
	A3-245	8/23/84	2308	2608R2	9708R2	X		
	A3-248	10/18/84	2308	0309R3	9505	X		

TABLE I. (Continued)

	TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
	A3-249	10/22/84	2308	0309R3	9505	X		X
	A3-250	01/18/85	2308	9106	9808	X		X
	A3-251	02/01/85	2308	9106	9808	X		X
	A3-252	02/09/85	2308	9106	9808	X		X
	A3-253	02/19/85	2308	2209R3	9505R1	X		X
	A3-254	2/22/85	2308	2209R3	9505R1	X	X	
	A3-255	02/26/85	2308	9106R1	9505R1	X	X	X
	A3-256	3/1/85	2308	9106R1	9505R1	X		X
	A3-257	3/6/85	2308	9106R2	9505R1	X	X	X
	A3-258	3/23/85	2308	9106R2	2606R4	X		X
	A3-259	3/27/85	2308	9106R2	2606R4	X		X
	A3-261	9/13/85	2025	5103	2021R1	X	X	
	A3-262	10/12/58	2025	5103	6001R1	X		X
	FRF14E3	06/02/84	2017	2018	9110	X		
	FRF51JE1	9/12/85	2011	5301	2022R2	X		
	FRF51JE2	9/12/85	2019	2120	9211R2	X		
	FRF51JE3	9/12/85	2017	2218R1	4102R1	X		
H	STS02E1	11/12/81	2007	9006R1	$\boxed{0007R1}$	X		
	STS02E2	11/12/81	2006	0306R1	2404	X		
	STS02E3	11/12/81	2005	0009R1	2105	X		
H	STS03E1	3/22/82	2007	9006R1	$\boxed{0007R1}$	X		
	STS03E2	03/11/82	2006	0306R1	2404	X		
	STS03E3	3/22/82	2005	0009R1	2105R1	X		
H	STS04E1	6/27/82	2007	2009	$\boxed{0007R1}$	X		
	STS04E2	6/27/82	2006	0306R1	2404	X		
	STS04E3	6/27/82	2005	0009R1	2105R1	X		
	STS05E1	11/11/82	2007	2009	9009R3	X		
	STS05E2	11/11/82	2006	0306R2	2404	X		
	STS05E3	11/11/82	2005	9006R2	2105R1	X		
	STS06E1	4/3/83	2017	9110	9010	X	X	
	STS06E2	4/3/83	2015	2315	2015	X	X	

TABLE I. (Continued)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
STS06E3	4/3/83	2012	2213	2016	X	X	
STS07E1	6/18/83	2017	2315	9010	X	X	
STS07E2	06/18/83	2015	9211	2015	X	X	
STS07E3	06/18/83	2012	2213	2016	X	X	
STS08E1	2/20/81	2017	2315	9010	X		
STS08E2	2/20/81	2015	9211	2015	X		
STS08E3	2/20/81	2012	2116R2	2016	X		
STS11E1	2/3/84	2109	5101R1	2020	X		
STS11E2	2/3/84	2015	9211	2015	X		
STS11E3	2/3/84	2012	2116R2	2016	X		
STS13E1	4/6/84	2109	5101R1	2020	X	X	
STS13E2	4/6/84	2020	2018	2021	X	X	
STS13E3	4/6/84	2012	2116R3	2016	X	X	
STS41DE1	08/30/84	2109	2020R1	2020	X	X	
STS41DE2	08/30/84	2018	2017R1	9211	X	X	
STS41DE3	08/30/84	2021	4001R1	4001	X	X	
STS41GE1	10/5/84	2023	2515R1	2019R1	X		
STS41GE2	10/5/84	2020	9311R1	2021	X		
STS41GE3	10/5/84	2021	4001R1	4001	X		
STS51AE1	11/8/84	2109	2020R1	2020	X	X	
STS51AE2	11/08/84	2018	2017R2	9211	X	X	
STS51AE3	11/08/84	2012	2118	9110	X	X	
STS51BE1	4/30/85	2023	2515R1	2019R1	X	X	
STS51BE2	4/30/85	2020	9311R1	2021	X	X	
STS51BE3	4/30/85	2021	2216	4001	X	X	
STS51CE1	01/24/85	2109	4202	2020	X	X	
STS51CE2	01/24/85	2018	2017R2	2018R1	X	X	
STS51CE3	01/24/85	2012	4003	9110	X	X	
STS51DE1	4/13/85	2018	4202	2115	X		
STS51DE2	4/13/85	2018	2017R2	2018R1	X		
STS51DE3	4/13/85	2012	4003	9110	X		

TABLE I. (Concluded)

TEST #	DATE	ENG #	HPFTP #	HPOTP #	100	104	109
STS51FE1	7/29/85	2023	2515R1	2019R2	X	X	
STS51FE2	7/29/85	2020	4202R1	4003R2	X	X	
STS51FE3	7/29/85	2021	2216	4001R1	X	X	
STS51IE1	8/27/85	2109	2121R1	2115	X	X	
STS51IE2	08/27/85	2018	4201R2	2016R3	X	X	
STS51IE3	08/27/85	2012	4003R1	2018R2	X	X	
STS51JE1	10/3/85	2011	5301	2022R2	X	X	
STS51JE2	10/3/85	2019	2120	9211R2	X	X	
STS51JE3	10/3/85	2017	2218R1	4102R1	X	X	
STS61AE1	10/30/85	2023	2515R1	2019R2	X	X	
STS61AE3	10/30/85	2021	2216	2020R3	X	X	

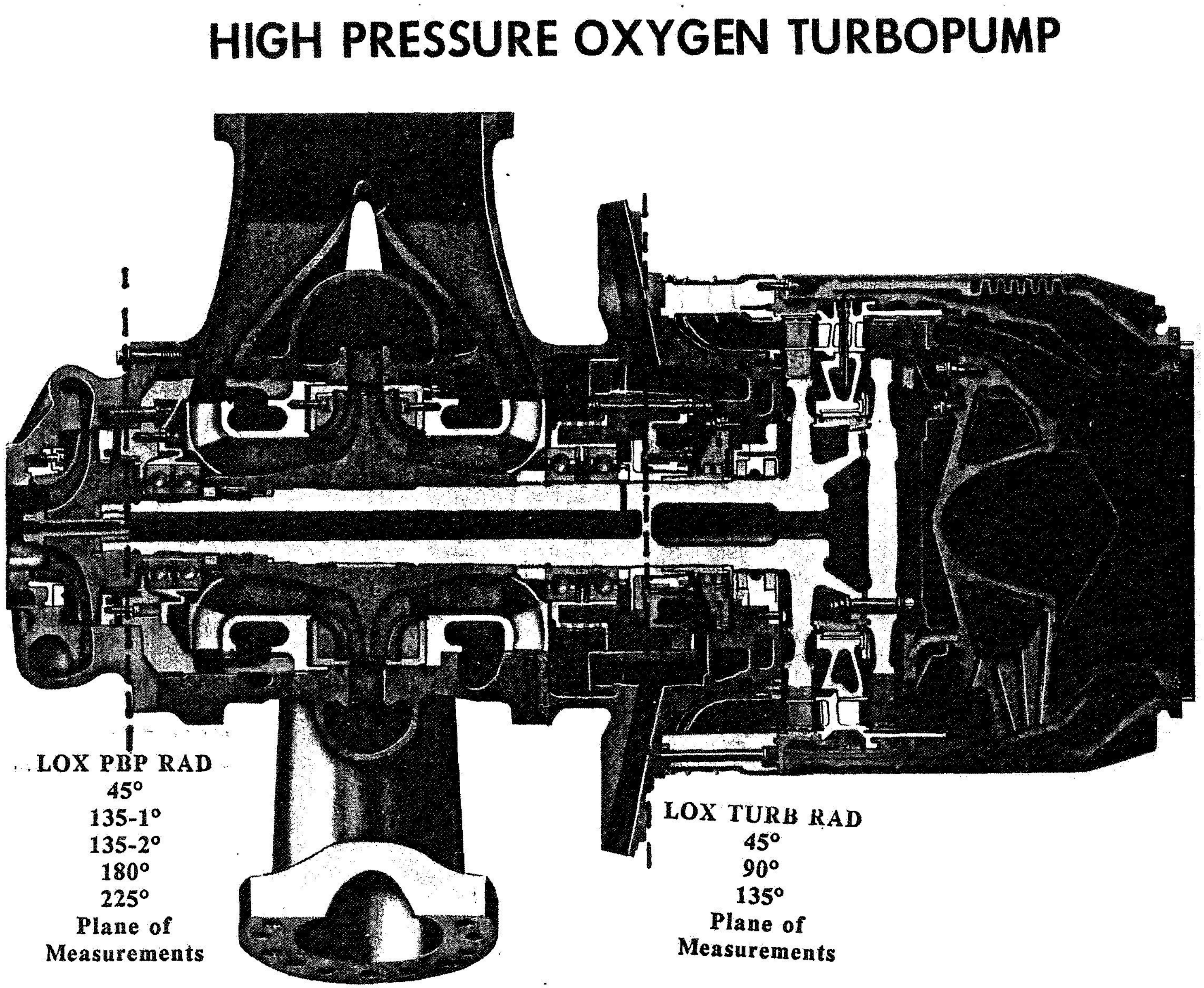

Figure 1. Accelerometer Location Plane HPOTP

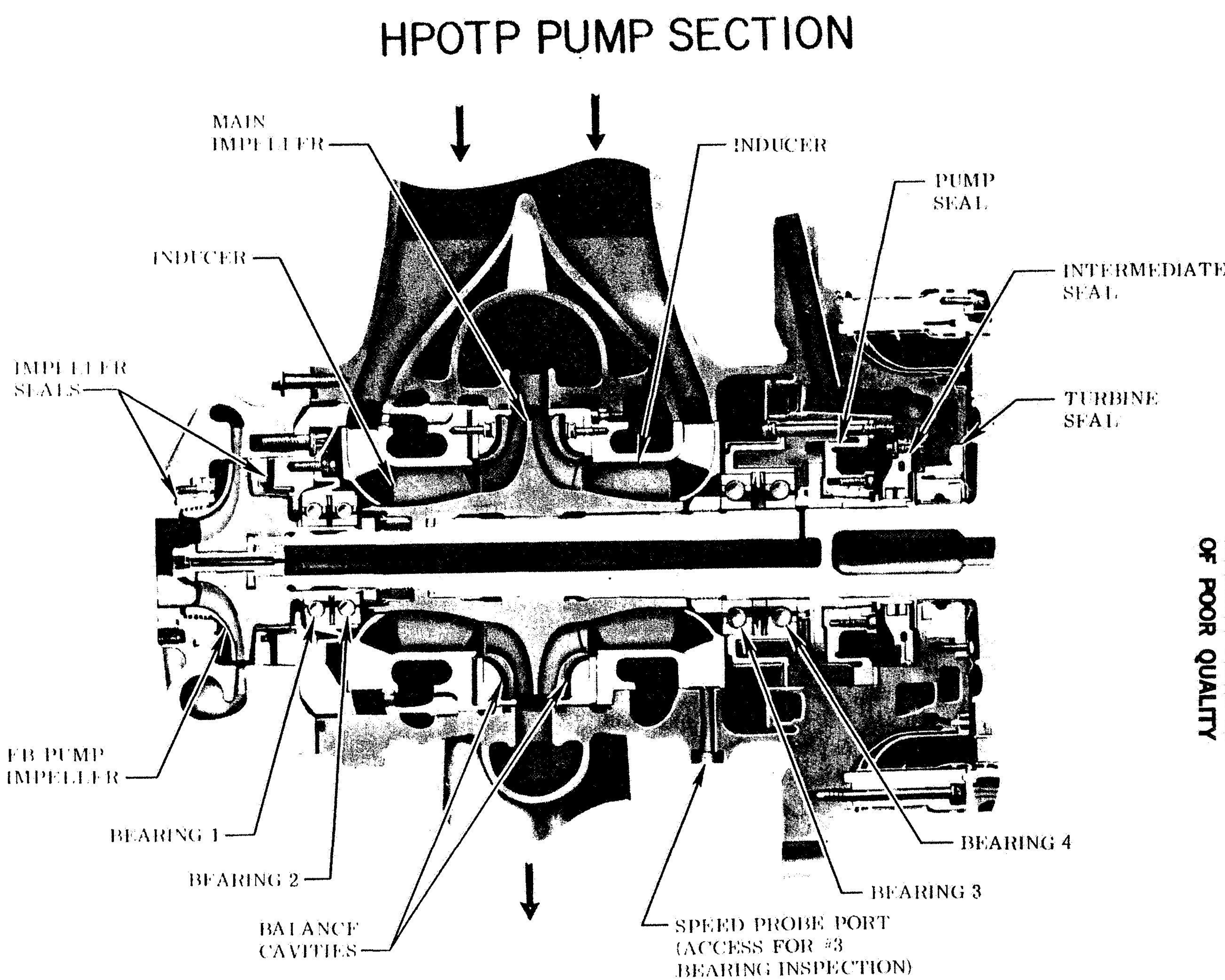

Figure 2. Major Components of HPOTP Pump

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2.3 Total Data Base HPOTP Synchronous Vibration

All tests listed in Table I were used to generate the plots shown in Figures 3 to 14. Separate plots are shown for 100%, 104%, and 109% power levels. These plots are the cumulative and density histograms of all the relevant synchronous Grms vibration data presently in the MSFC Diagnostic Data Base. Immediately obvious, especially at the 104% power level, is the bi-modal type of distribution which indicates the possibility of two different data groups. Also of note is the fact that a bi-modal type of distribution <u>does not</u> appear on the turbine end vibration measurements.

In the last quarter of 1982 a major effort was instigated to evaluate the second group of tests i.e. tests with synchronous levels greater than approximately 4 Grms. Numerous MSFC and contractor personnel were involved in the effort and investigated different facets of the problem such as imbalance, tear down inspection records, common components, etc. for each vibration data group. The conclusion from the original study was that the increased synchronous vibration levels were associated with the HPOP Main Impeller.

2.4 Listing of Suspect Main Impeller

The results of the MSFC/NASA investigation specifically identified six main impellers common to the second data group of tests, i.e. tests with synchronous vibration levels greater than 4 Grms. A total of 33 main impellers were investigated. The serial numbers, tests, power levels and the serial number of the HPOTP where the main impeller was installed are shown in Tables II through VII. These tables are a modified version of output of a computer routine available within NASA/MSFC for tracking components of the SSME.

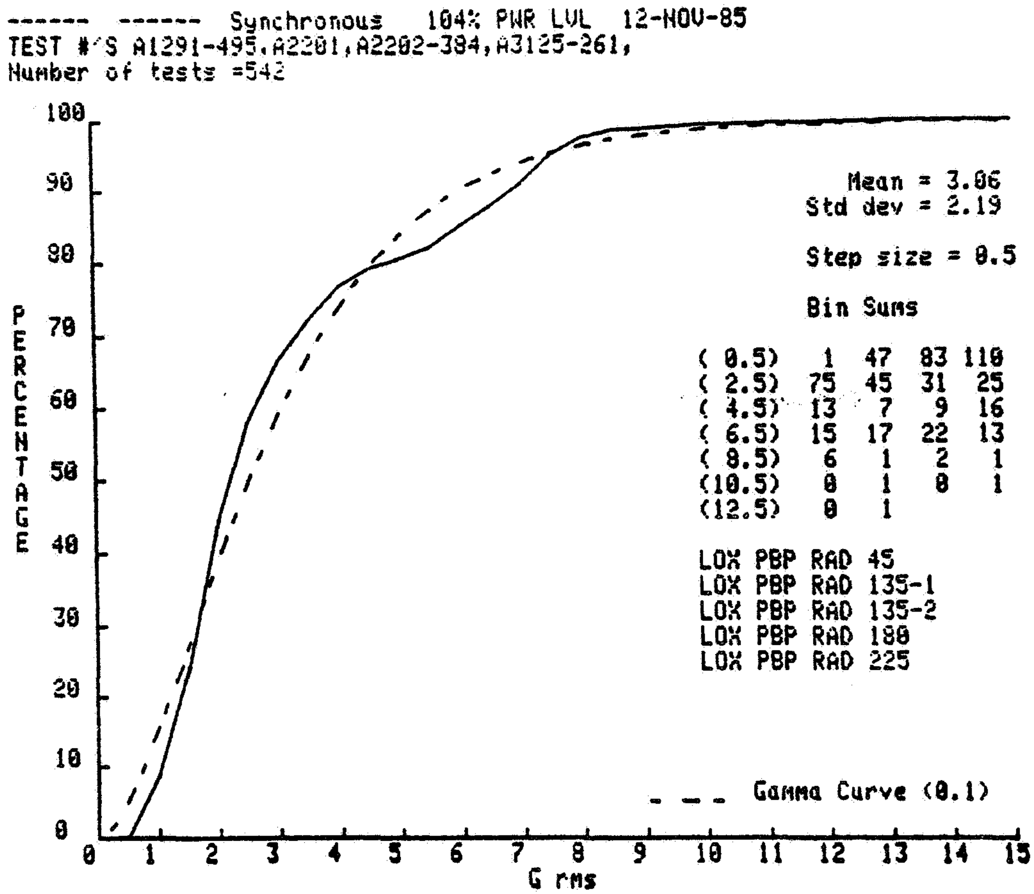

Figure 3. Cumulative Distribution HPOTP-PBP Total Data Base 104%

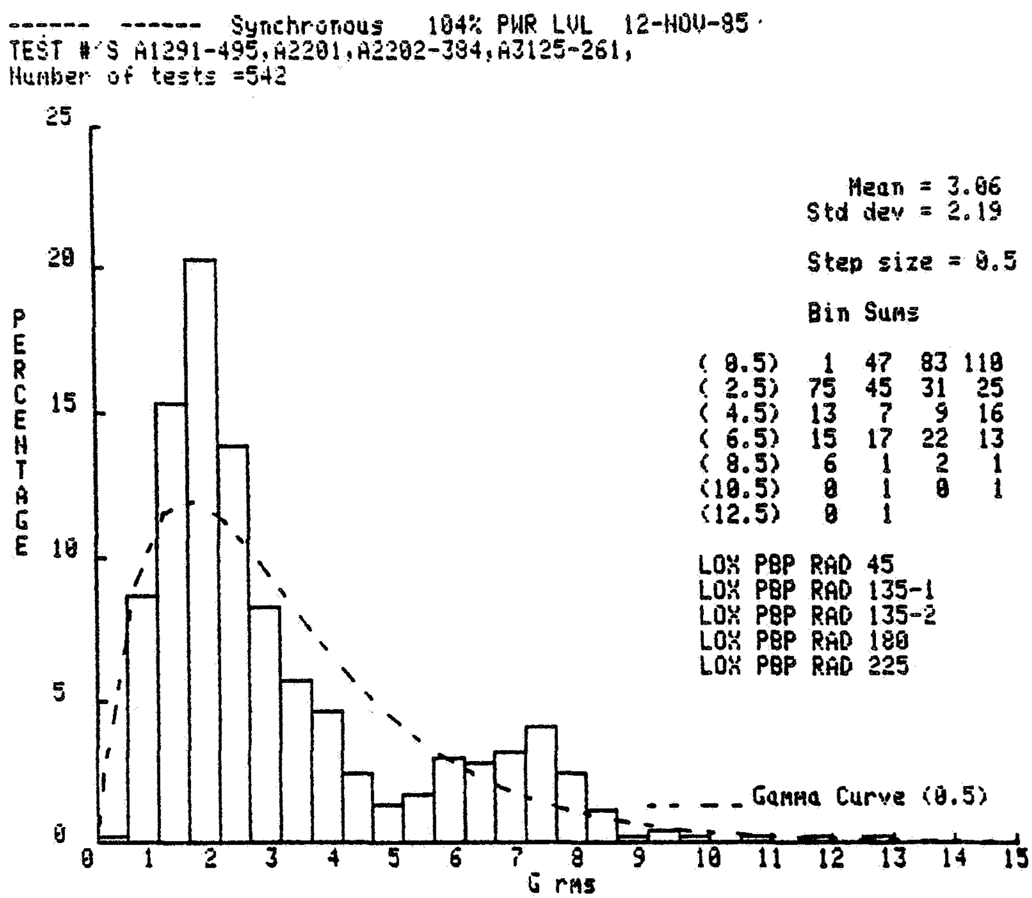

Figure 4. Probability Density HPOTP-PBP Total Data Base 104%

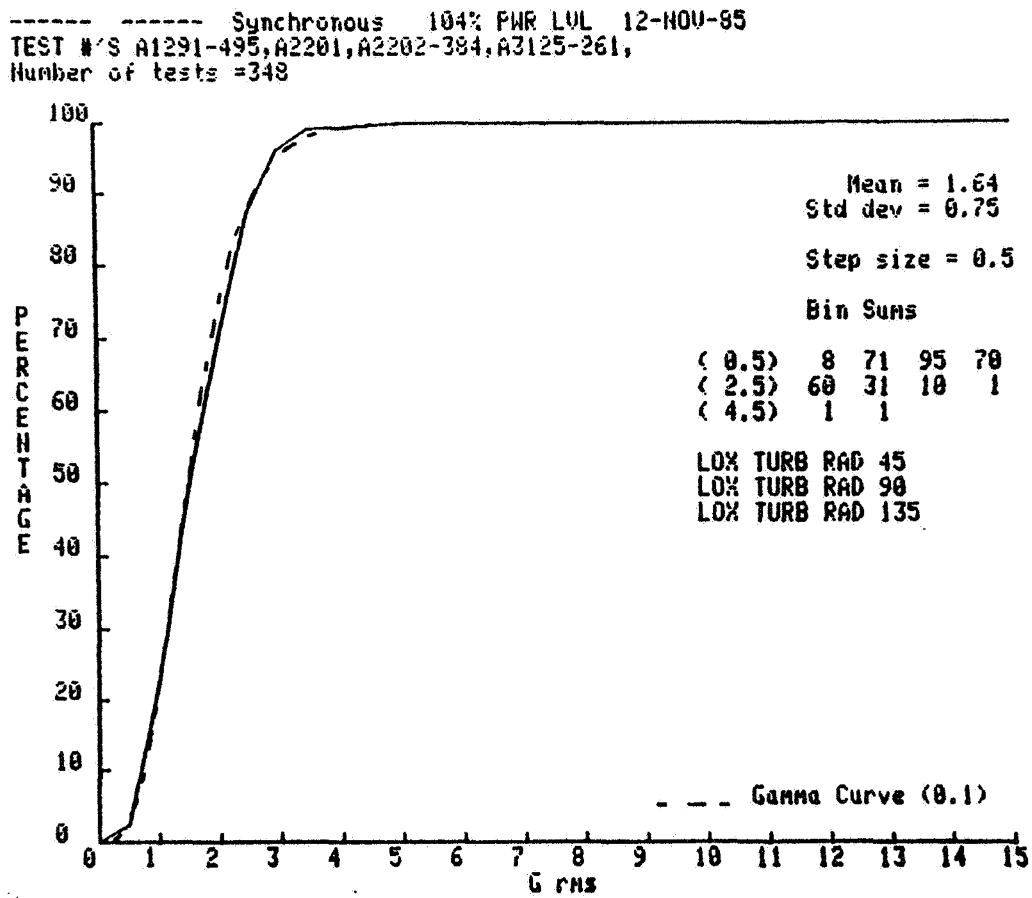

Figure 5. Cumulative Distribution HPOTP-TURB Total Data Base 104%

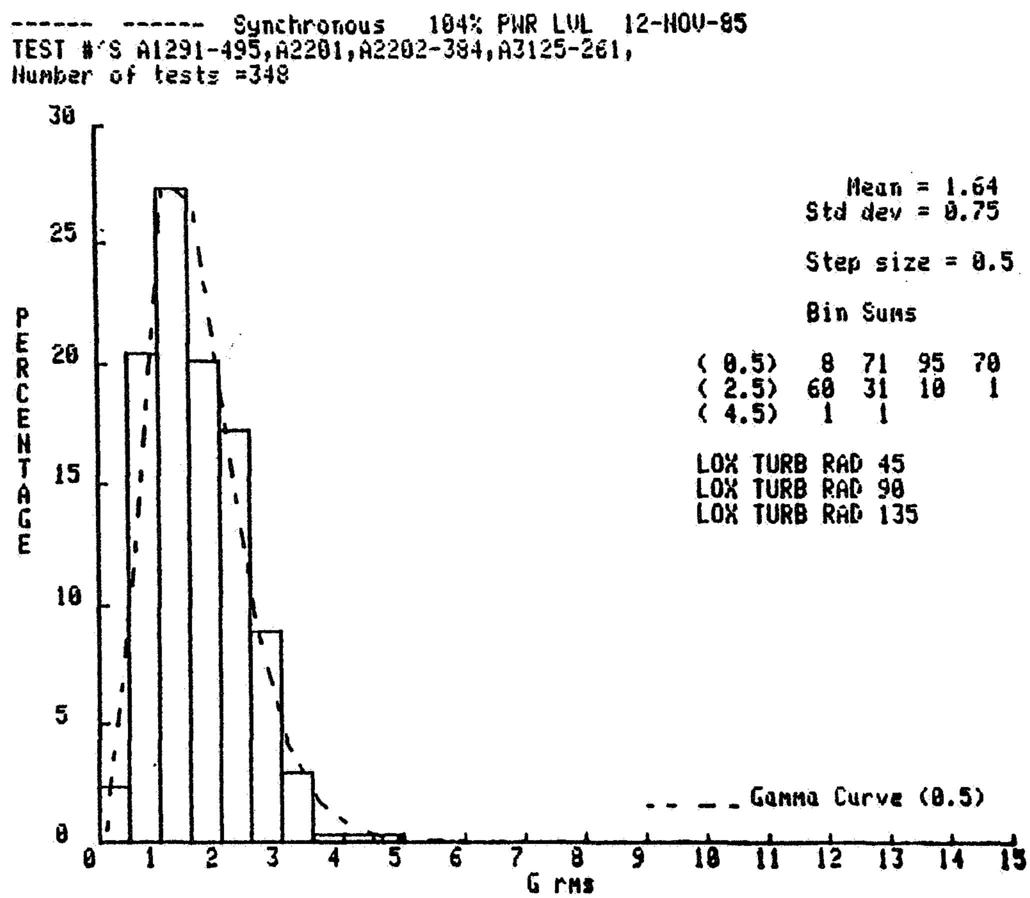

Figure 6. Probability Density HPOTP-TURB Total Data Base 104%

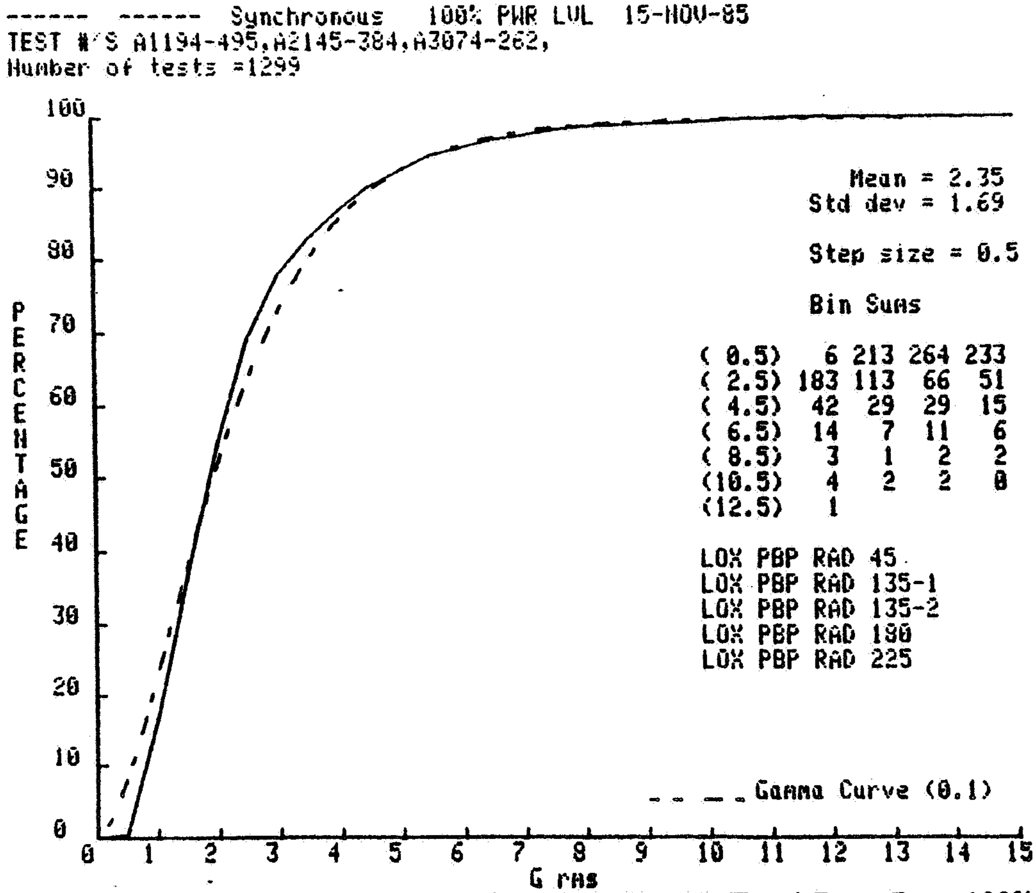

Figure 7. Cumulative Distribution HPOTP-PBP Total Data Base 100%

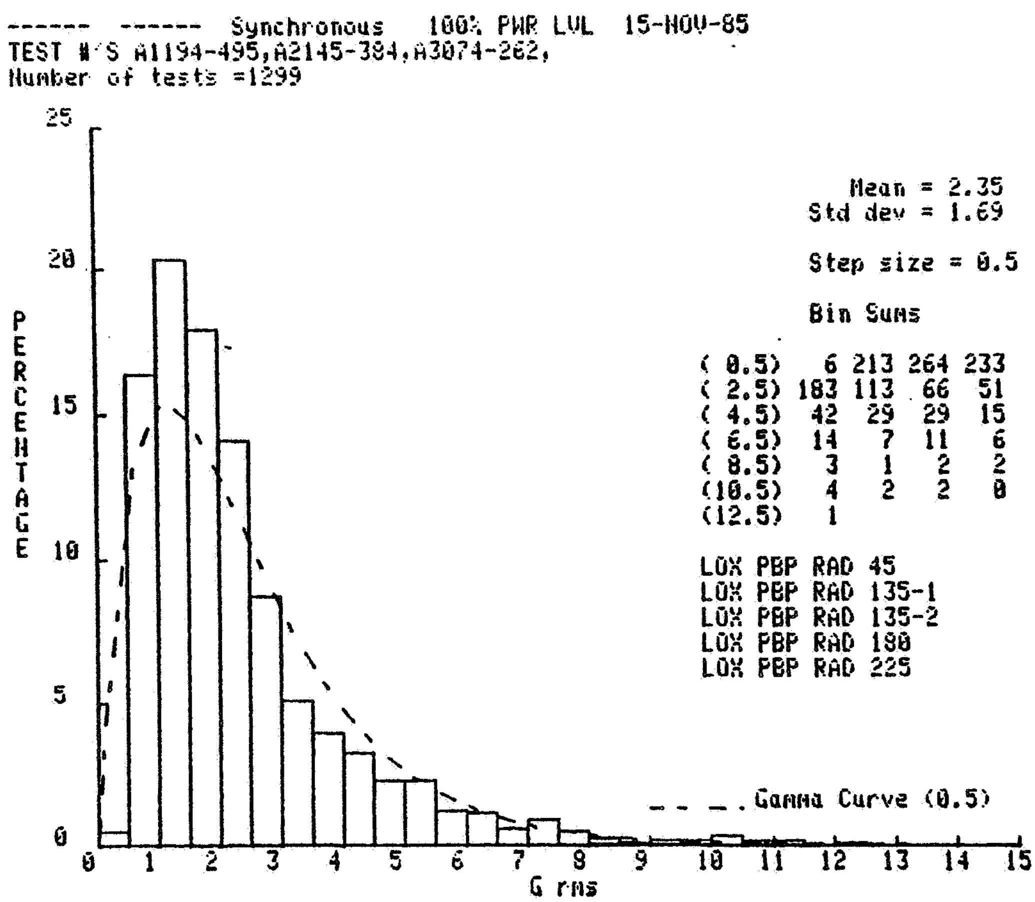

Figure 8. Probability Density HPOTP-PBP Total Data Base 100%

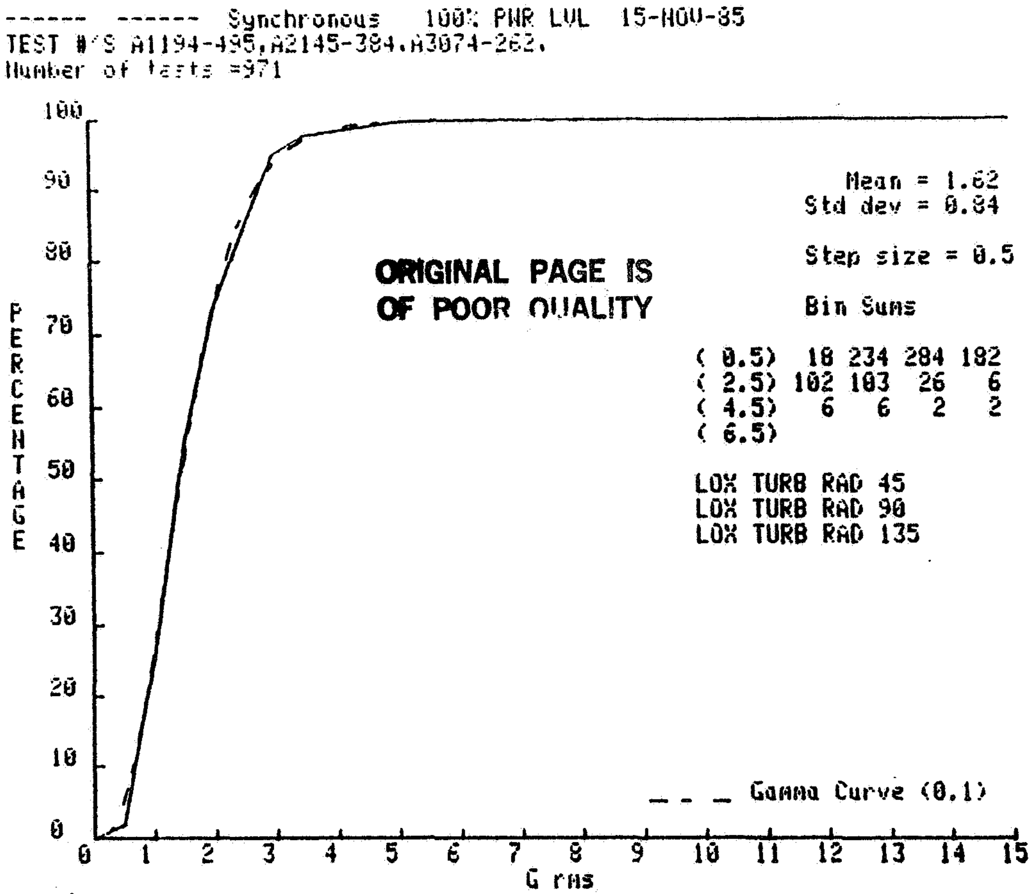

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Figure 9. Cumulative Distribution HPOTP-TURB Total Data Base 100%

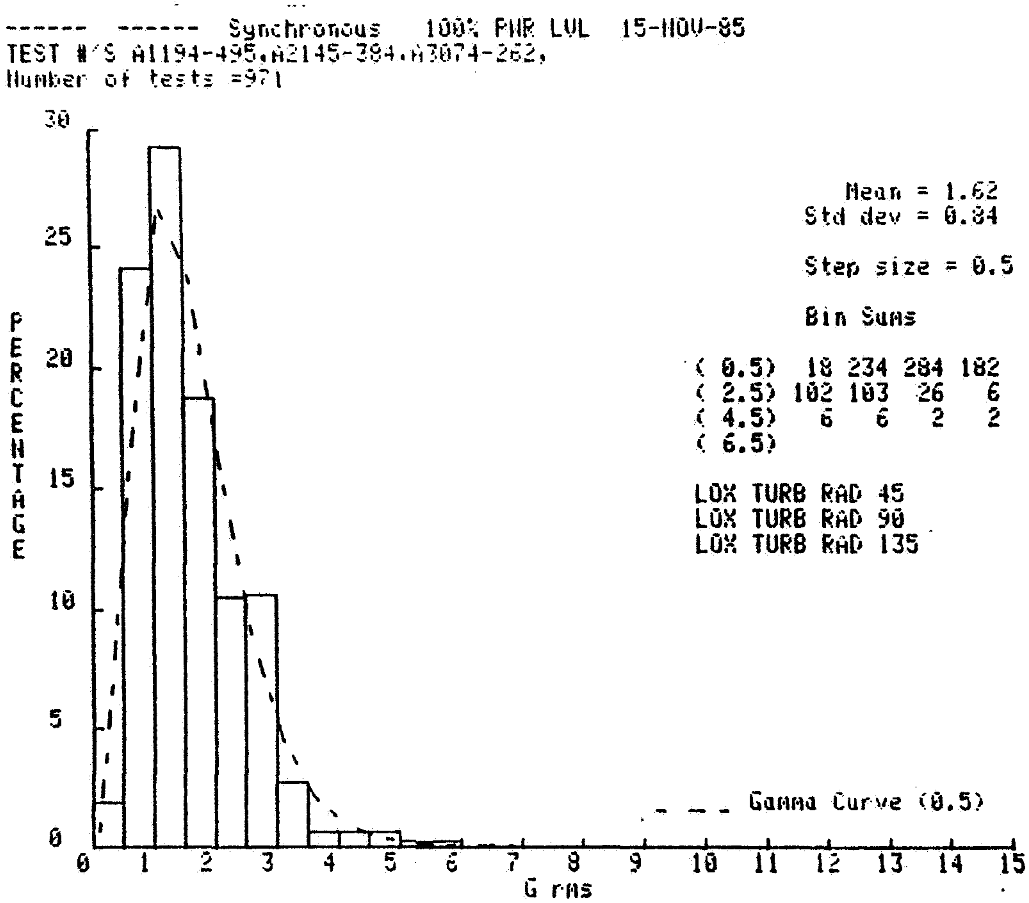

Figure 10. Probability Density HPOTP-TURB Total Data Base 100%

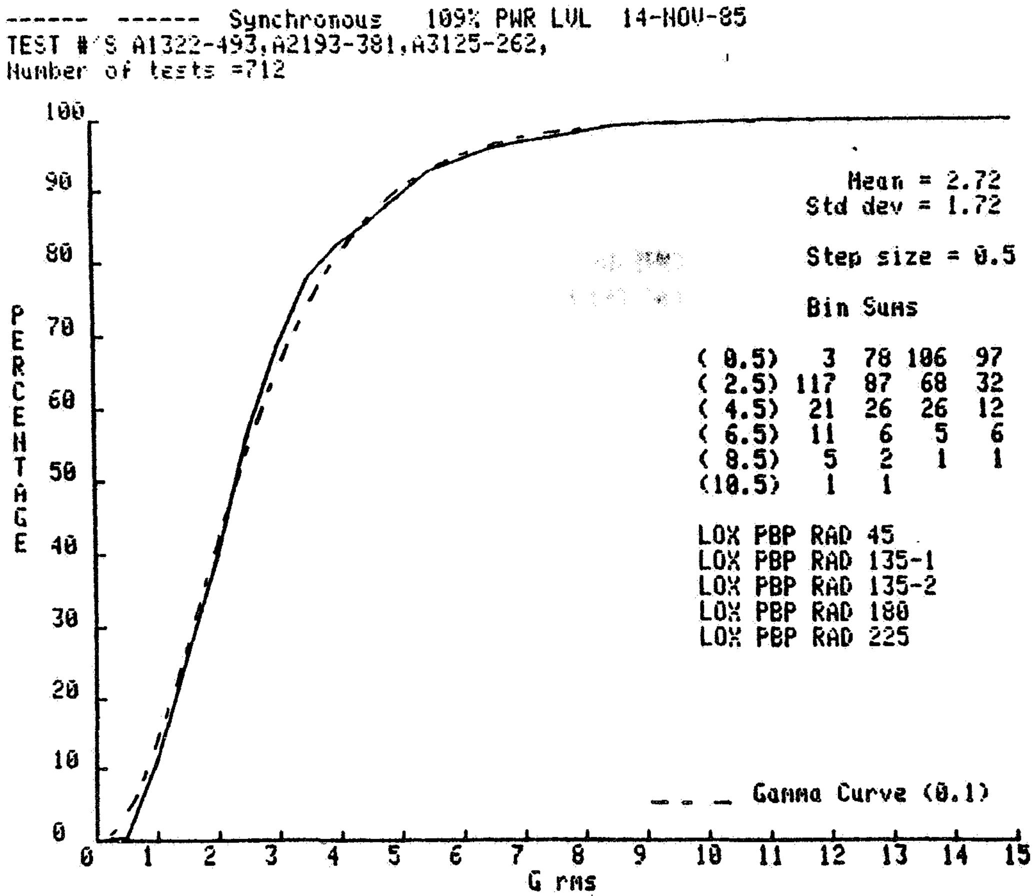

Figure 11. Cumulative Distribution HPOTP-PBP Total Data Base 109%

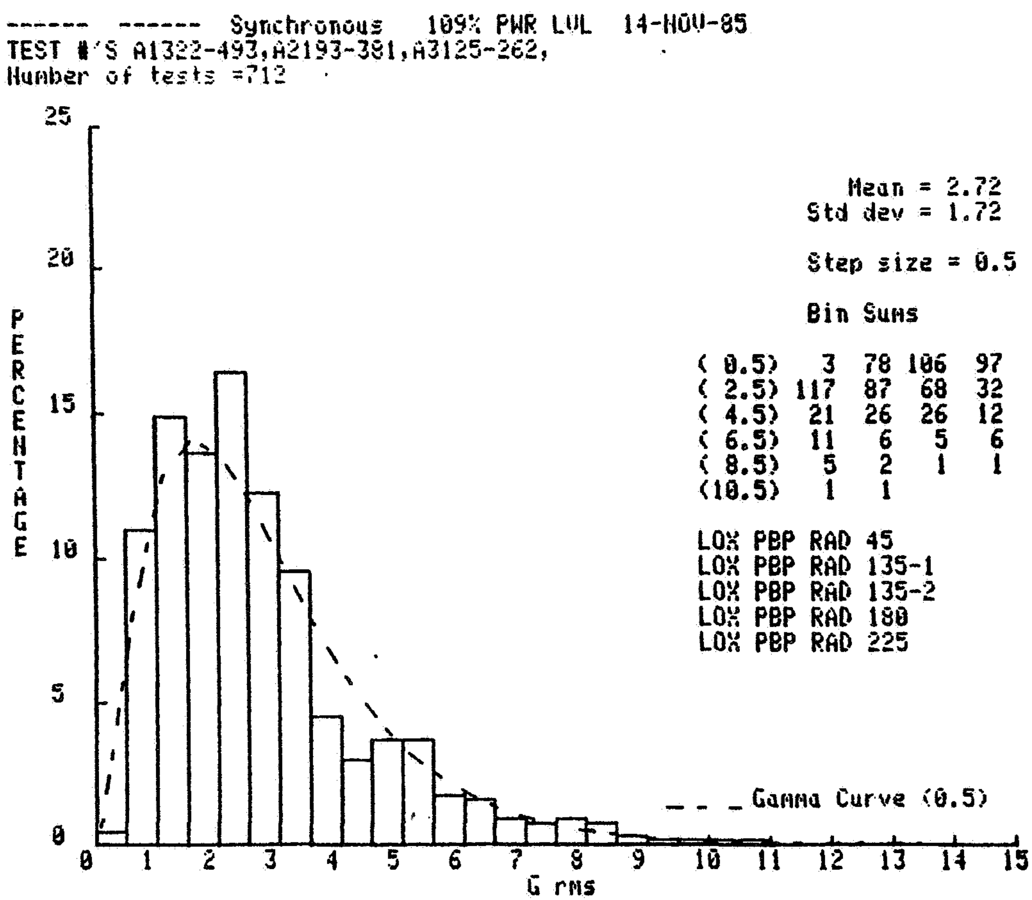

Figure 12. Probability Density HPOTP-PBP Total Data Base 109%

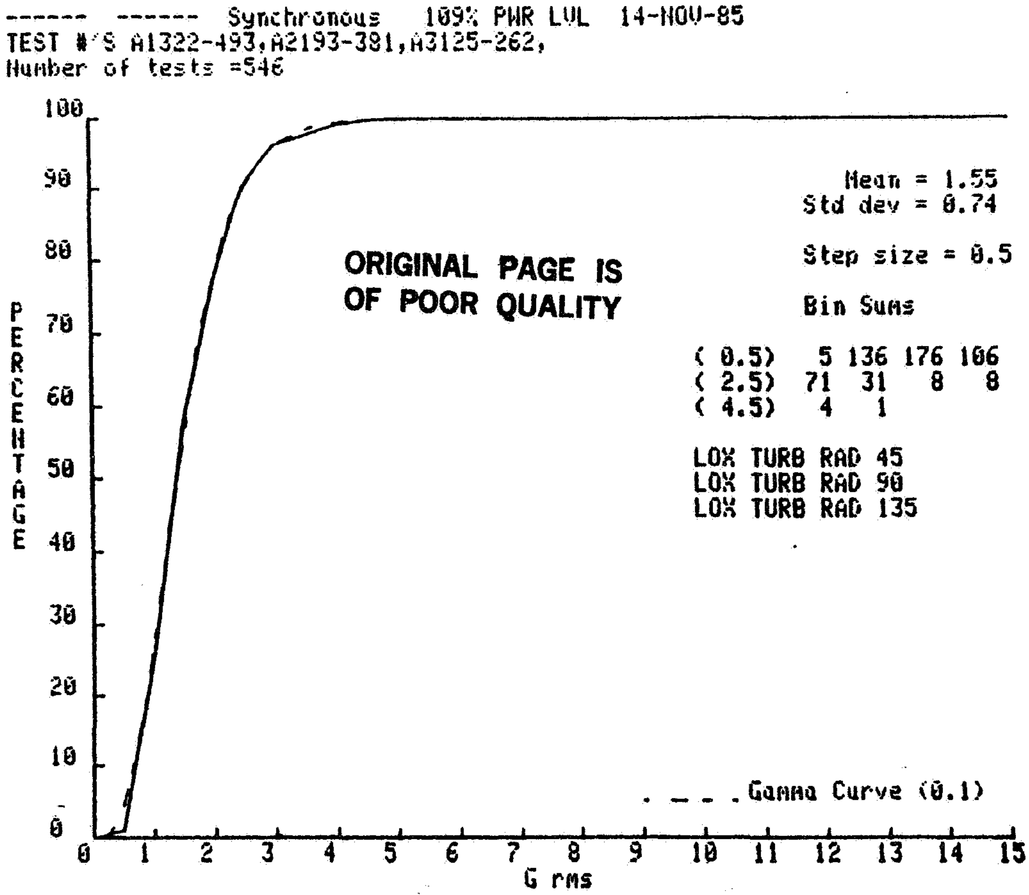

Figure 13. Cumulative Distribution HPOTP-TURB Total Data Base 109%

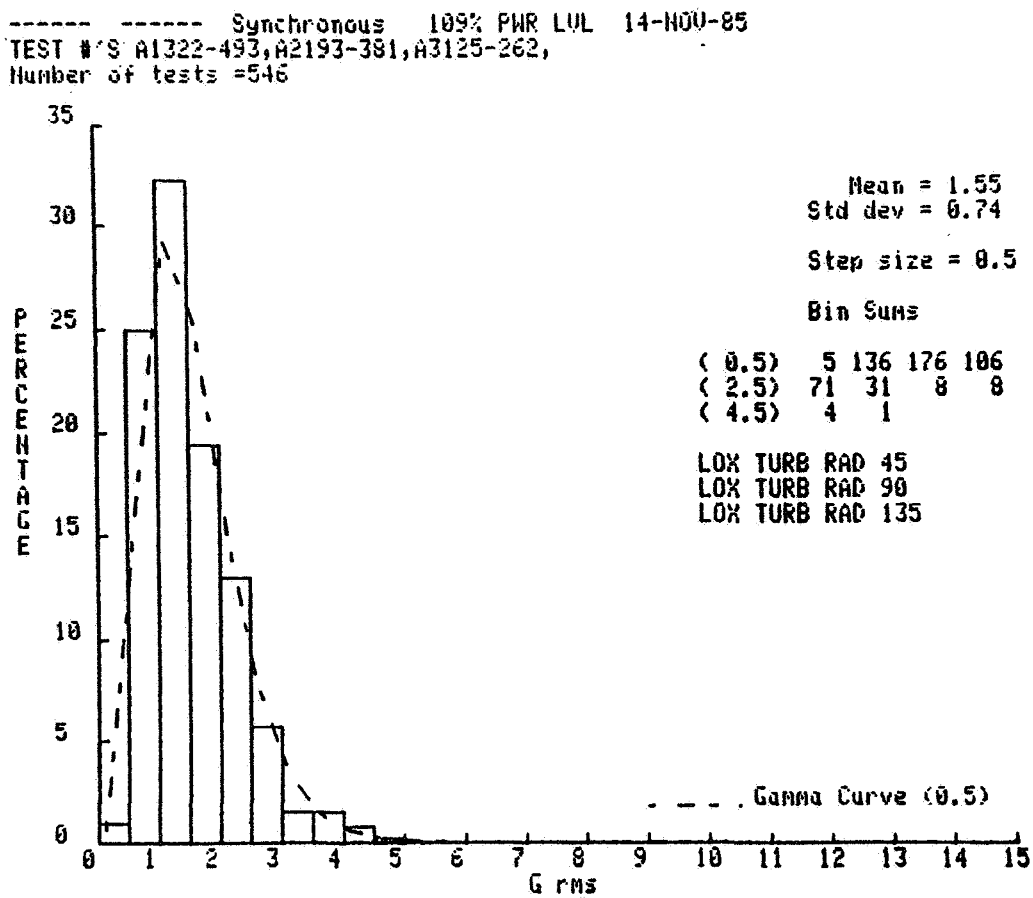

Figure 14. Probability Density HPOTP-TURB Total Data Base 109%

TABLE II. HPOP MAIN IMPELLER HISTORY - S/N 2427800

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-043

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
2108	82/02/01	901357	500.00	25.74	0.10	449.20	19.80
2108	82/02/08	901358	500.00	25.68	0.10	469.20	0.00
2108R1	82/02/19	902265	100.00	95.86	0.00	0.00	0.00
2108R1	82/02/22	902266	500.00	6.56	1.94	380.10	0.00
2108R2	82/06/18	902278	1.50	0.00	0.00	0.00	0.00
2108R2	82/06/20	902279	50.00	4.90	0.20	30.10	0.00
2108R2	82/06/28	902280	1.50	0.00	0.00	0.00	0.00
2108R2	82/06/29	902281	1.50	0.00	0.00	0.00	0.00
2108R2	82/07/01	902282	1.50	0.00	0.00	0.00	0.00
2108R2	82/07/03	902283	50.00	4.90	0.20	30.10	0.00
2108R2	82/07/09	902284	500.00	6.43	1.94	380.20	0.00
2108R2	82/07/13	902285	10.00	5.75	0.00	0.00	0.00
2108R2	82/07/27	750169	1.49	0.00	0.00	0.00	0.00
2108R2	82/07/29	750170	50.00	35.78	0.00	0.00	0.00
2108R2	82/08/04	750171	299.89	14.92	0.20	270.10	0.00
2108R2	82/08/07	750172	300.00	14.87	0.20	270.10	0.00
2312	82/10/18	901392	1.50	0.00	0.00	0.00	0.00
2312	82/10/21	901393	51.00	46.76	0.00	0.00	0.00
2412	83/01/28	750189	3.65	0.00	0.00	0.00	0.00
2412	83/02/04	750190	250.00	64.89	139.80	9.60	0.00
2412	83/03/23	750193	70.00	5.50	50.10	0.00	0.00
2412	83/04/14	750194	16.84	5.36	6.94	0.00	0.00
2412	83/04/22	750195	300.00	7.15	240.20	0.00	0.00
2412	83/05/02	750196	150.00	64.89	59.70	0.00	0.00
2412	83/05/16	750197	320.00	7.23	240.20	0.00	0.00
2412	83/05/23	750198	320.00	8.74	240.20	0.00	0.00
2412	83/05/28	750199	190.00	35.30	140.10	0.00	0.00
2412	83/06/04	750200	190.00	25.23	150.10	0.00	0.00
2412	83/06/09	750201	100.00	5.47	80.10	0.00	0.00
2412	83/06/21	750202	2.20	0.00	0.00	0.00	0.00
2412	83/06/25	750203	100.00	5.46	80.10	0.00	0.00
2412	83/06/30	750204	320.02	7.17	240.20	0.00	0.00
2412	83/07/06	750205	320.00	7.16	240.20	0.00	0.00
2412	83/07/11	750206	320.00	22.84	224.80	0.00	0.00
2412	83/07/21	750207	100.00	20.60	74.70	0.00	0.00
Total S/N 2427800			5992.68	581.14	2212.32	2288.70	19.80

TABLE III. HPOP MAIN IMPELLER HISTORY - S/N 3134124

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-043

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
2109	81/11/14	901344	500.00	5.44	0.20	429.20	0.00
2109	81/11/18	901345	270.00	5.36	0.20	249.20	0.00
2109	81/11/19	901346	500.00	5.35	0.20	479.20	0.00
2109	81/11/30	901347	95.40	90.70	0.00	0.00	0.00
2109	81/12/02	901348	750.00	199.53	0.20	509.20	0.00
2109	81/12/04	901349	463.58	5.15	0.10	452.78	0.00
2111	82/03/15	902268	500.00	6.32	1.94	380.20	0.00
2111	82/03/23	902269	500.00	6.14	1.94	1.94	380.20
2111	82/03/29	902270	250.00	4.69	0.10	240.10	0.00
2211	82/05/15	901365	1.50	0.00	0.00	0.00	0.00
2211	82/05/19	901366	100.00	95.83	0.00	0.00	0.00
2311	82/12/05	901396	1.50	0.00	0.00	0.00	0.00
2311	82/12/07	901397	100.00	85.80	0.00	0.00	0.00
2311	82/12/14	901398	500.00	6.57	1.94	380.20	0.00
2311	82/12/18	901399	500.00	6.58	1.94	380.20	0.00
2311	82/12/23	901400	500.00	6.76	1.94	380.20	0.00
2311R1	83/01/22	901403	50.00	35.88	0.00	0.00	0.00
2311R1	83/01/28	901404	250.00	4.92	0.20	230.10	0.00
2311R1	83/02/04	901405	500.00	6.58	1.94	380.20	0.00
Total S/N 3134124			6331.98	577.60	12.84	4542.71	380.20

TABLE IV. HPOP MAIN IMPELLER HISTORY - S/N 3134446

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-043

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
2212	82/06/30	901374	500.00	6.64	1.94	380.20	0.00
2212	82/06/07	901375	50.00	35.83	0.00	0.00	0.00
2212	82/07/10	901376	5.12	0.00	0.00	0.00	0.00
2212	82/07/14	901377	300.00	295.89	0.00	0.00	0.00
2212	82/07/23	901378	1.50	0.00	0.00	0.00	0.00
2212	82/07/25	901379	50.00	4.88	0.20	30.10	0.00
2212	82/07/27	901380	500.00	6.60	1.94	380.20	0.00
2212	82/07/30	901381	500.00	6.58	1.94	380.20	0.00
2212	82/08/02	901382	500.00	6.33	1.94	1.94	380.20
2212R1	82/08/18	750173	41.76	4.86	0.10	31.86	0.00
2208	83/04/08	902308	1.50	0.00	0.00	0.00	0.00
2208	83/04/14	902309	4.95	0.39	0.00	0.00	0.00
2208	83/04/18	902310	190.00	95.93	79.70	0.00	0.00
2208	83/08/02	750208	320.00	6.97	240.20	0.00	0.00
2208	83/08/08	750209	320.00	7.54	240.00	0.00	0.00
2208	83/10/05	750216	70.00	15.20	40.10	0.00	0.00
2208	83/10/11	750217	300.00	285.45	0.00	0.00	0.00
2208	83/10/18	750218	300.00	15.00	270.10	0.00	0.00
2208	83/10/24	750219	300.00	15.07	270.10	0.00	0.00
2208R1	83/12/29	901431	1.50	0.00	0.00	0.00	0.00
2208R1	84/01/04	901432	190.00	95.95	79.70	0.00	0.00
Total S/N 3134446			4446.33	905.11	1227.96	1204.50	380.20

TABLE V. HPOP MAIN IMPELLER HISTORY - S/N 3135444

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-043

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
0110	82/06/06	902277	250.00	4.94	0.20	225.10	0.00
0110R1	82/09/13	901386	1.54	0.00	0.00	0.00	0.00
0110R1	82/09/19	901387	1.50	0.00	0.00	0.00	0.00
0110R1	82/09/21	901388	5.40	0.92	0.00	0.00	0.00
0110R1	82/09/25	901389	120.00	95.82	9.70	0.00	0.00
0210	82/12/08	750183	299.95	85.78	124.20	85.05	0.00
0210R1	83/01/11	902305	1.50	0.00	0.00	0.00	0.00
0210R1	83/01/13	902306	86.44	82.28	0.00	0.00	0.00
0210R2	83/03/02	750192	39.89	5.21	29.99	0.00	0.00
Total S/N 3135444			806.22	274.95	164.09	310.15	0.00

TABLE VI. HPOP MAIN IMPELLER HISTORY - S/N 7326708

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-049

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
0007	80/01/22	901263	1.50	0.00	0.00	0.00	0.00
0007	80/01/24	901264	1.50	0.00	0.00	0.00	0.00
0007	80/01/25	901265	1.50	0.00	0.00	0.00	0.00
0007R1	80/02/11	750065	1.50	0.00	0.00	0.00	0.00
0007R1	80/02/12	750066	300.00	248.38	0.00	0.00	0.00
0007R1	80/02/22	750067	300.00	254.34	0.00	0.00	0.00
0007R1	80/06/16	901282	520.00	424.34	0.00	0.00	0.00
0007R1	81/02/20	FRF001-A	21.86	15.26	0.00	0.00	0.00
0007R1	81/04/12	STS001-A	519.42	432.45	0.00	0.00	0.00
0007R1	81/11/12	STS002-A	520.13	435.78	0.00	0.00	0.00
0007R1	82/03/22	STS003-A	519.67	435.66	0.00	0.00	0.00
0007R1	82/06/27	STS004-A	519.03	443.06	0.00	0.00	0.00
0007R2	82/08/15	901383	300.00	295.85	0.00	0.00	0.00
0107	83/11/04	902320	1.50	0.00	0.00	0.00	0.00
0107	83/11/09	902321	1.50	0.00	0.00	0.00	0.00
0107	83/11/11	902322	190.00	95.77	79.70	0.00	0.00
Total S/N 7326708			5022.71	3353.93	352.08	59.44	0.00

TABLE VII. HPOP MAIN IMPELLER HISTORY - S/N 7363066

HPOP Main Impeller Histories Data as of November 4, 1985 - P/N RS007718-043

HPOTP	Test Date	Tests	NOMDUR	100% PWR	104% PWR	109% PWR	111% PWR
9011	82/10/23	902300	1.50	0.00	0.00	0.00	0.00
9011	82/10/25	902301	4.60	0.20	0.00	0.00	0.00
9111	83/01/04	901401	500.00	6.49	1.94	380.20	0.00
9111	83/01/08	901402	250.00	4.95	0.20	230.10	0.00
9111R1	83/02/12	750191	250.00	4.88	0.40	208.30	0.00
Total S/N 7363066			1006.10	16.52	2.54	818.60	0.00

2.5 Synchronous Vibration Data of Six Main Impellers

The next step in the investigation was to repeat the analysis with the six main impeller vibration test data separated from the data sample. The results are shown in Figures 15 to 22 at the 104% power level. These plots present a very strong implication of two distinct data groups and indicate the listed six main impellers as very suspect. This conclusion is based upon the obvious visual difference between the density histograms of Figures 4, 15 and 16. No elegant statistical mathematical methods are required. Also it should be noted that the cumulative distribution after removal of the suspect main impeller data provides a much better fit to the classical Gamma distribution discussed in Reference 1.[1] Figures 23 to 38 are the plots at 100% and 109% power level and also indicate a difference between groups, while not as dramatic as the 104% power level. Very little change appears in the LOX TURB RAD vibration cumulative distribution and probability density plots which is further evidence to suspect components on the preburner end of the turbopump. Since the purpose of this document is to record the results of the study, rather than a detailed discussion of statistical techniques and physical effects, a detailed analysis of each plot will not be addressed. The difference in the calculated mean Grms and standard deviation for the three data groups are listed in Table VIII.

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[1] Reference 1. Swanson, W. "Statistical Analysis of the Vibration Data for the SSME High Pressure Turbopump During Flight," Wyle TM 64058-01 October 1985.

TABLE VIII. LOX PBP RAD SYNCHRONOUS VIBRATION LEVELS

	Total Data Base	Six Main Impellers	Normal Operation
		100% Power Level	
Mean	2.35 Grms	4.61 Grms	1.89 Grms
Std Dev	1.69	2.16	1.12
Data Sample	1299	219	1080
		104% Power Level	
Mean	3.06 Grms	6.57 Grms	2.09 Grms
Std Dev	2.09	1.86	1.05
Data Sample	542	111	412
		109% Power Level	
Mean	2.72 Grms	5.42 Grms	2.15 Grms
Std Dev	1.72	2.14	1.03
Data Sample	712	114	576

Spatial Average LOX TURB RAD Synchronous

100% Power Level

	Total Data Base	Six Main Impellers	Normal Operation
Mean	1.62 Grms	2.07 Grms	1.55 Grms
Std Dev	0.84	1.08	0.76
Data Sample	971	138	833
		104% Power Level	
Mean	1.64 Grms	1.80 Grms	1.59 Grms
Std Dev	0.75	0.76	0.73
Data Sample	348	61	276
		109% Power Level	
Mean	1.55 Grms	1.70 Grms	1.52 Grms
Std Dev	0.74	0.82	0.73
Data Sample	546	82	449

Normal HPOTP Operation 104%

```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1291-323,A1390-430,A1433-440,A1446-495,A2201-307,A2311   -319,
A2323-326,A2329-343,A2345-354,A2357-374,A2383-384,A3125-181,A3211-215,A3
221-261,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

Six Main Impellers 104%

TESTS USED IN THIS ANALYSIS:

TEST #/S A1389, A1432, A1442-443, A2310, A2375-376, A3183-209, A3216-219

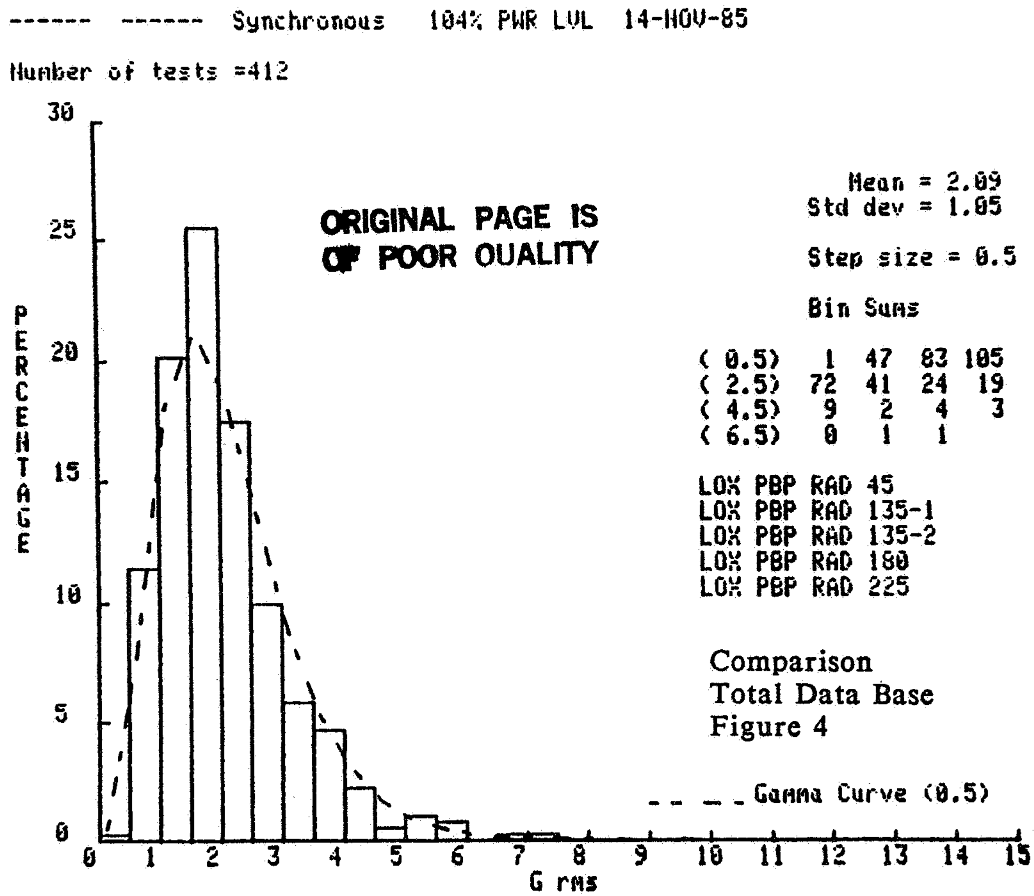


Figure 15. Probability Density for HPOTP-PBP Normal Operation 104%

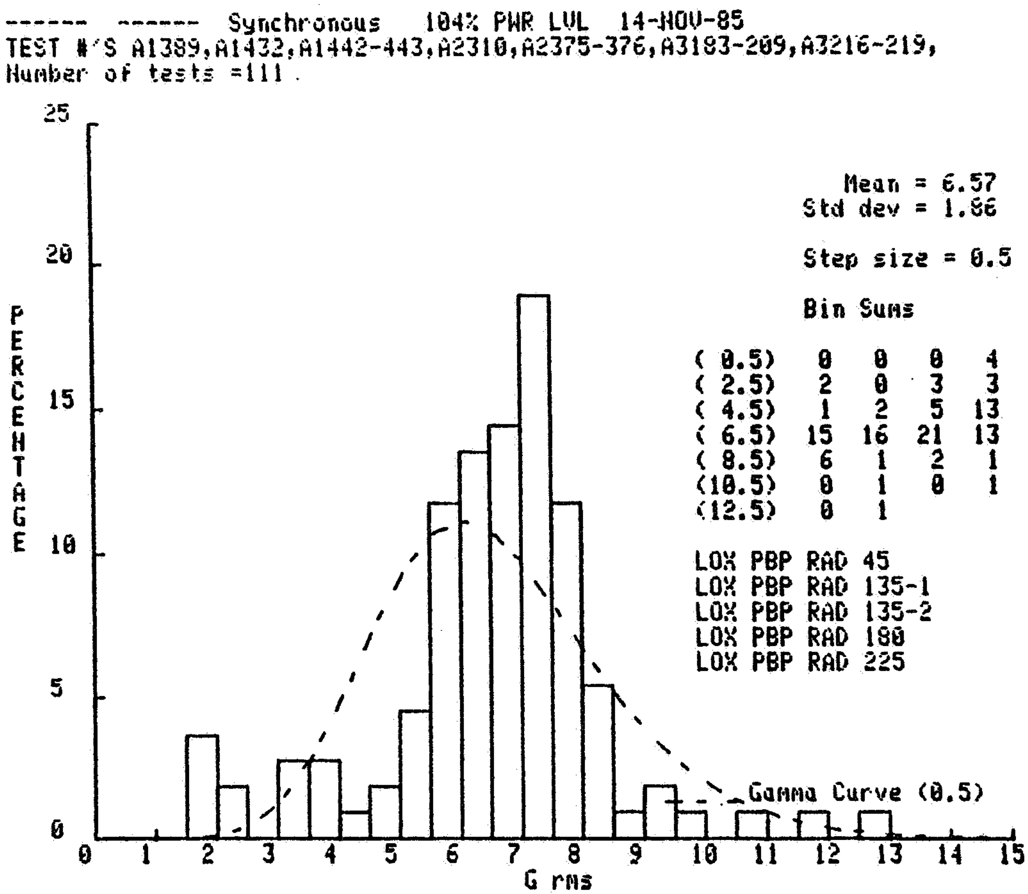


Figure 16. Probability Density for HPOTP-PBP Six Main Impellers 104%

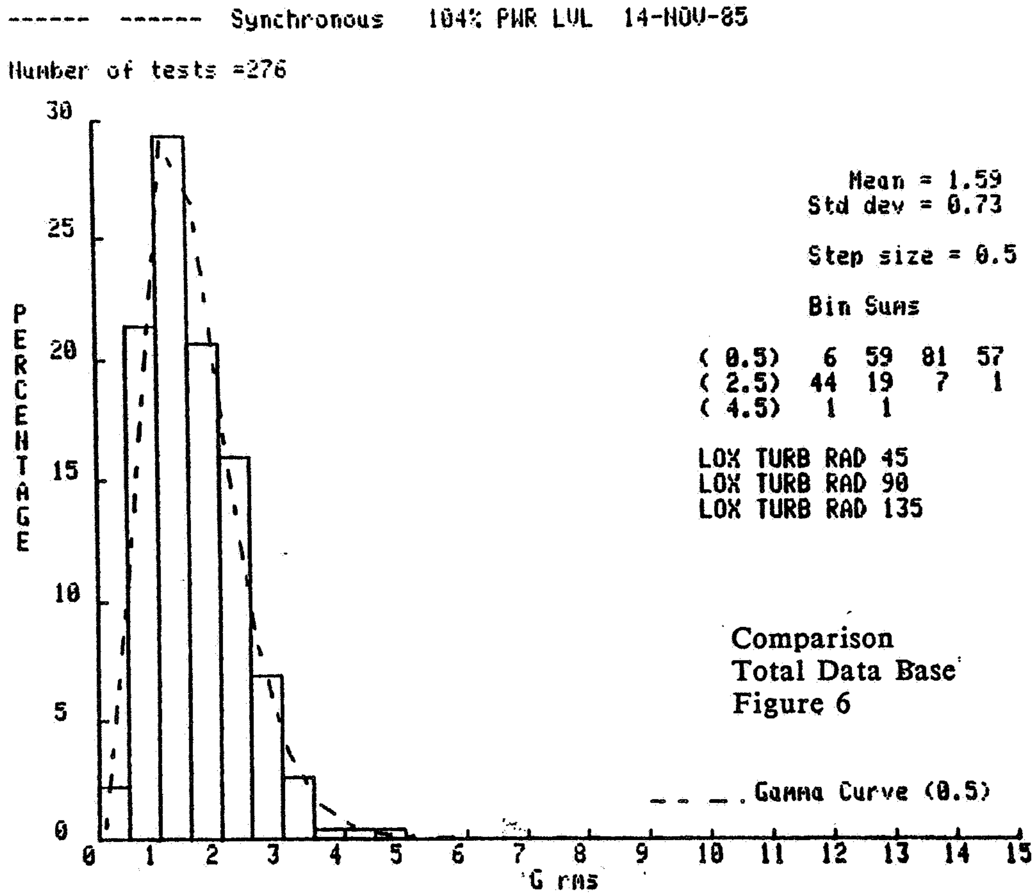


Figure 17. Probability Density HPOTP-TURB Normal Operation 104%

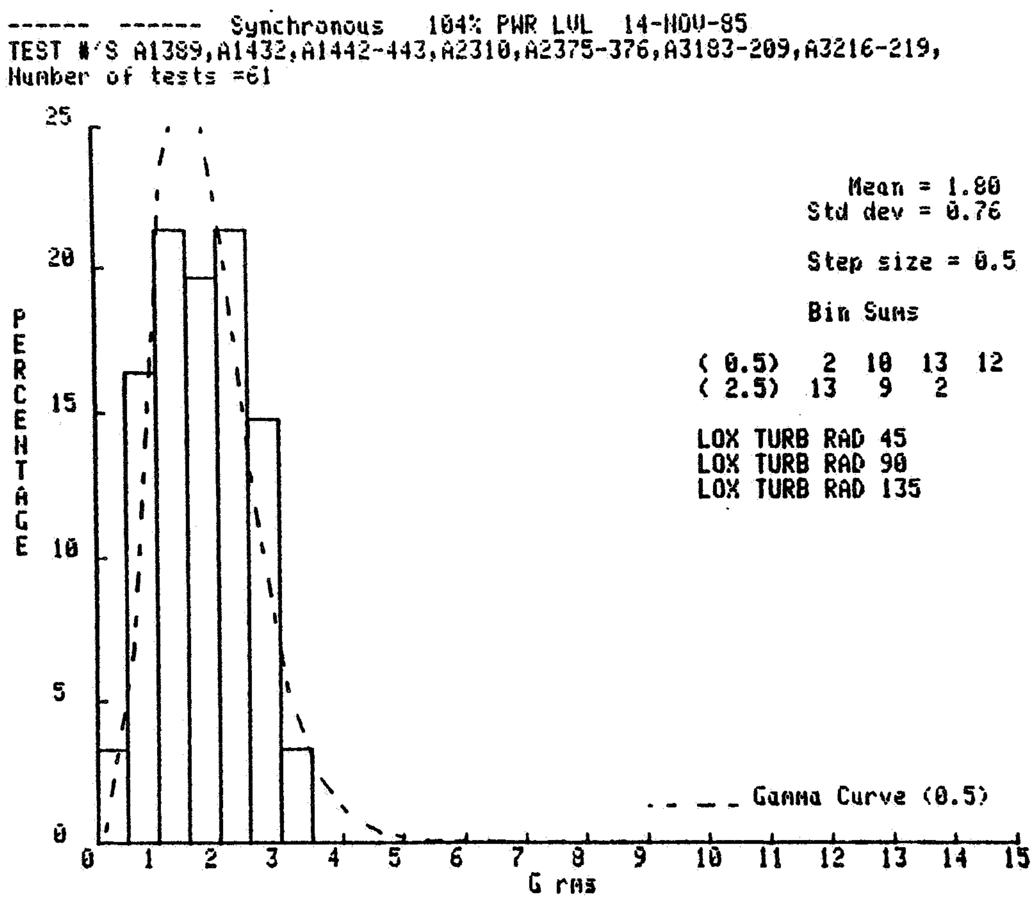


Figure 18. Probability Density HPOTP-TURB Six Main Impellers 104%

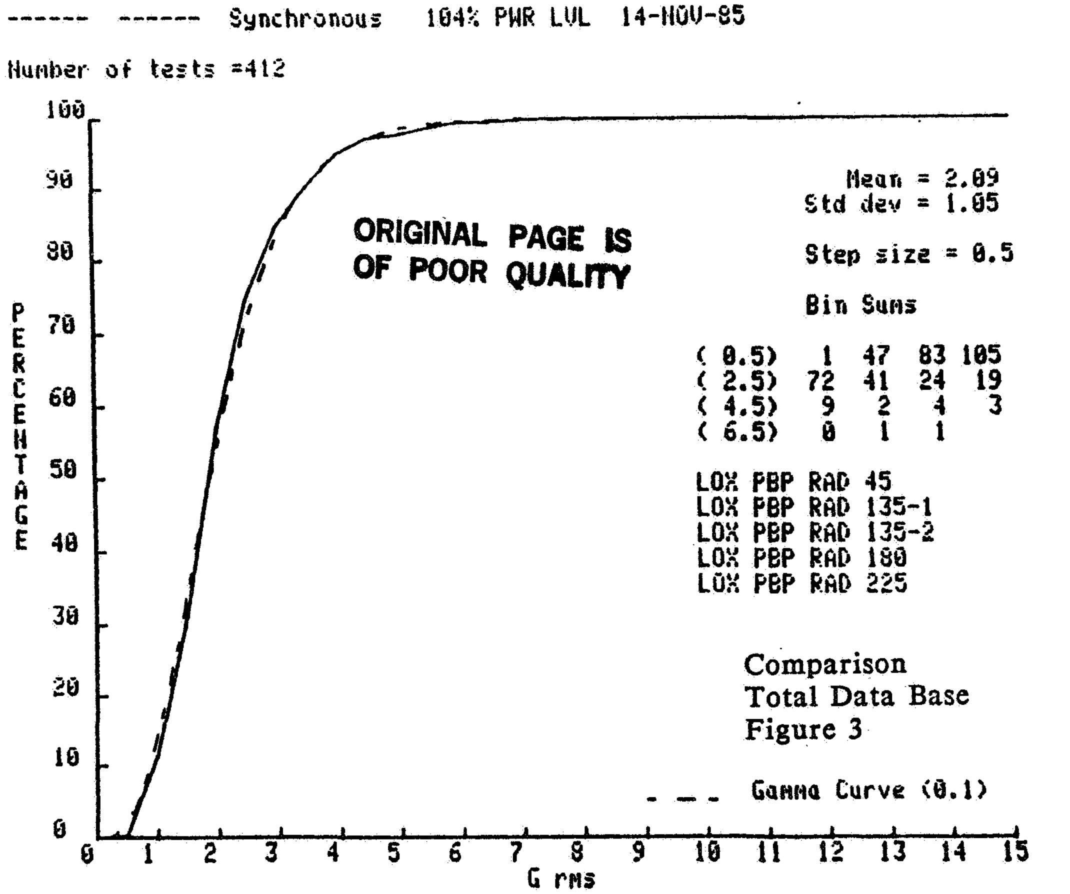


Figure 19. Cumulative Distribution HPOTP-PBP Normal Operation 104%

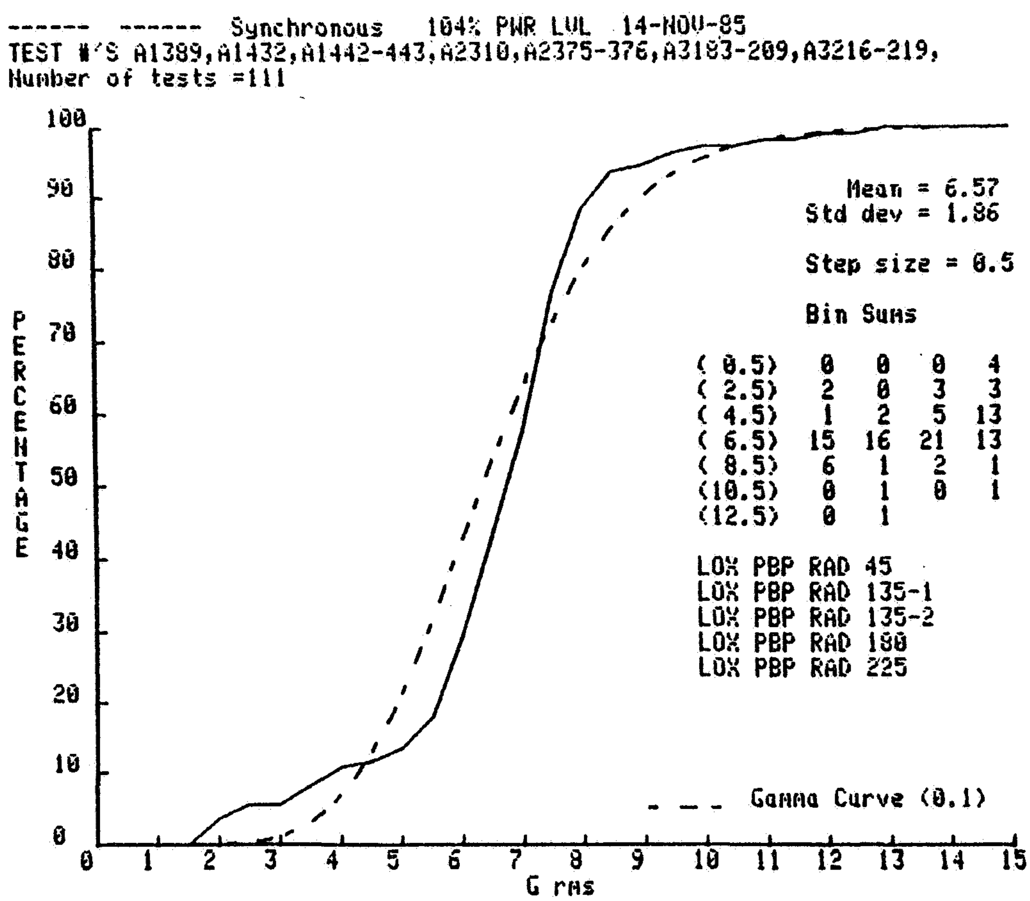


Figure 20. Cumulative Distribution HPOTP-PBP Six Main Impellers 104%

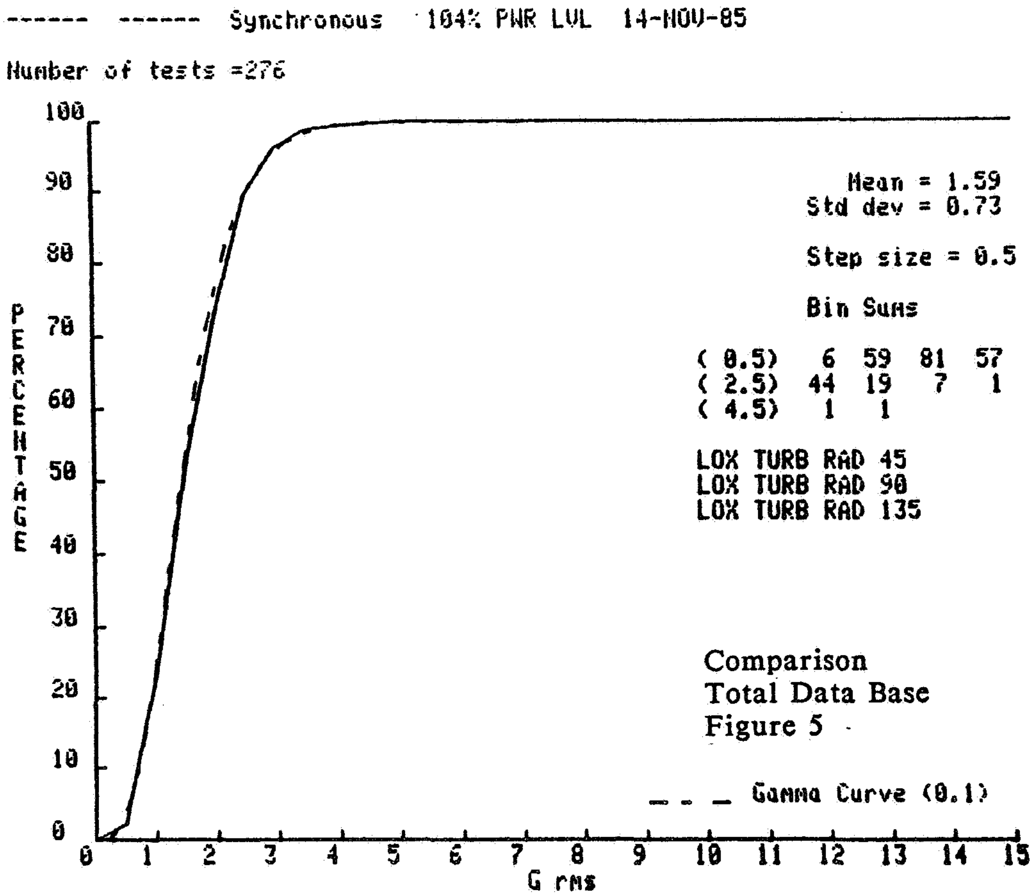


Figure 21. Cumulative Distribution HPOTP-TURB Normal Operation 104%

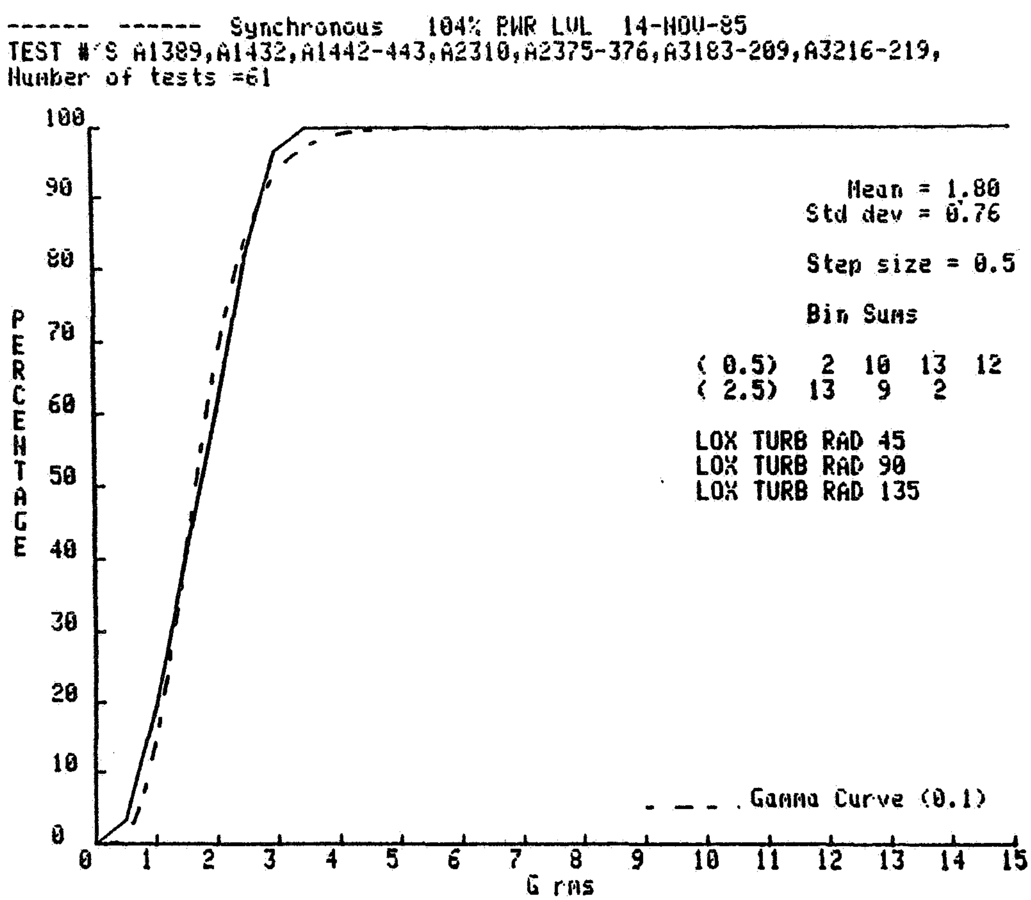


Figure 22. Cumulative Distribution HPOTP-TURB Six Main Impellers 104%

Normal HPOTP Operation 100%


```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1194-280,A1284-341,A1350-363,A1373,A1384,A1390-391,A1394-395,A
1406-430,A1433-440,A1445-495,A2145-264,A2271-274,A2289-303,A2307,A2311-3
19,A2323-374,A2377-384,A3074-162,A3177-182,A3184-188,A3210-215,A3220-262
,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

Six Main Impellers 100%

```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1282,A1347,A1366,A1375-383,A1389,A1393,A1397-405,A1432,A1442-4
44,A2265-268,A2285,A2306,A2309-310,A2322,A2375-376,A3170-173,A3183,A3190
-209,A3216-219,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
2
```

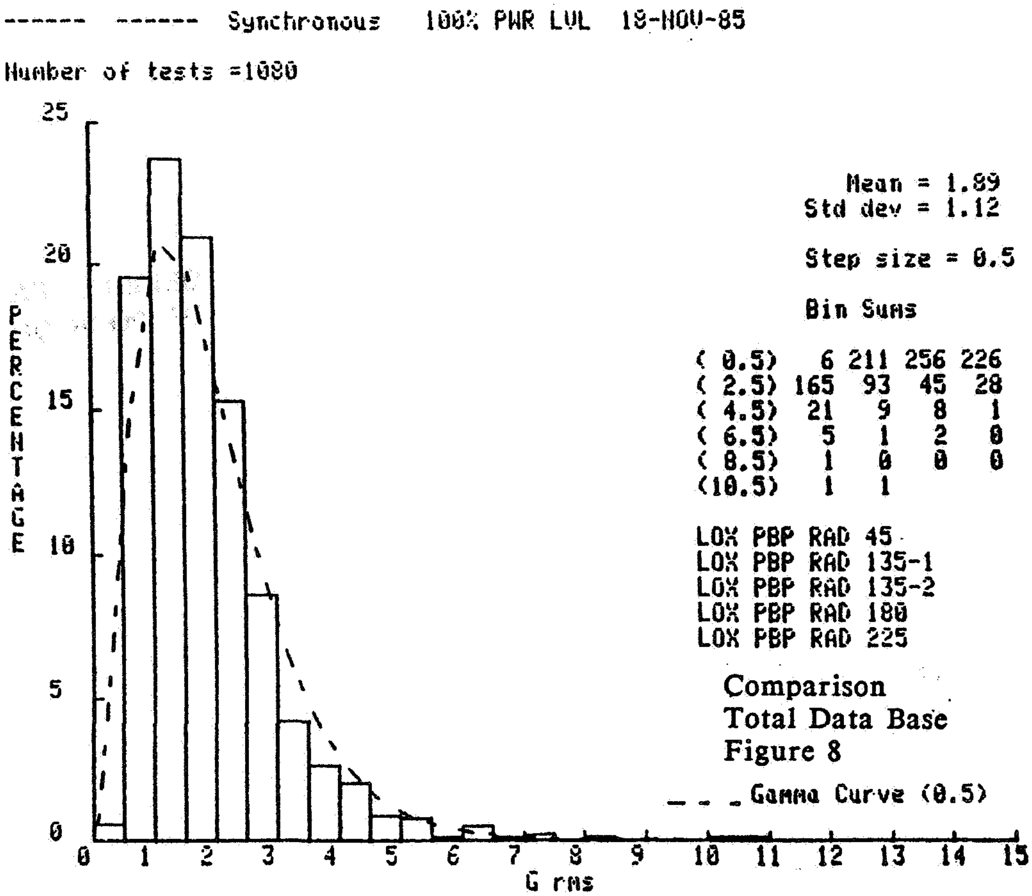


Figure 23. Probability Density HPOTP-PBP Normal Operation 100%

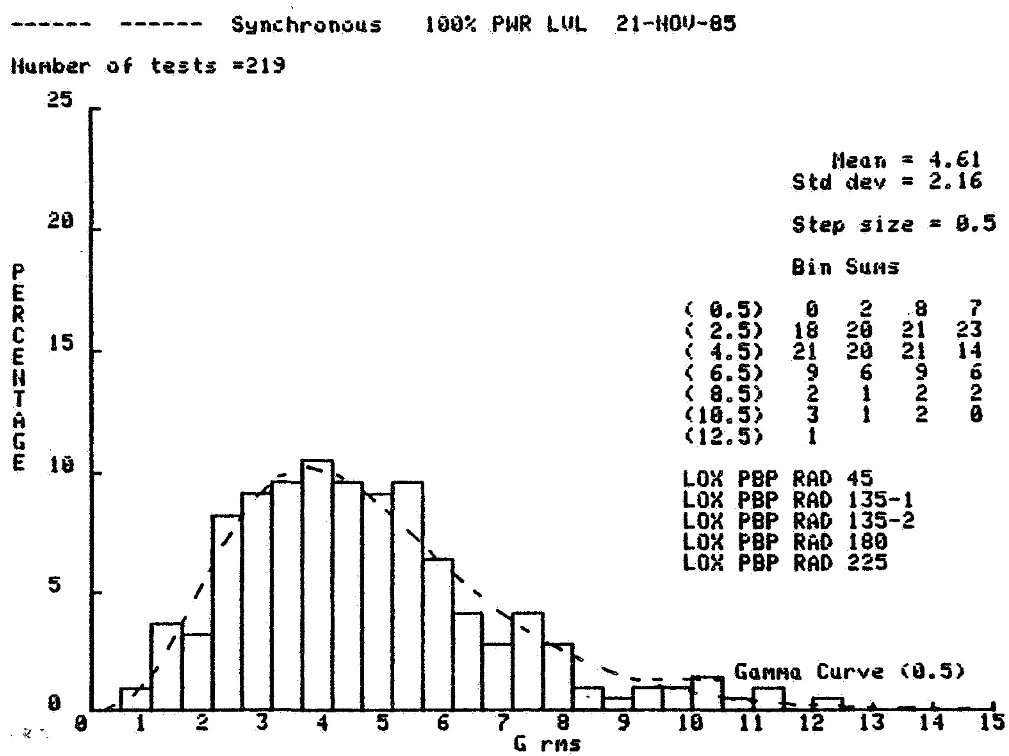


Figure 24. Probability Density HPOTP-PBP Six Main Impellers 100%

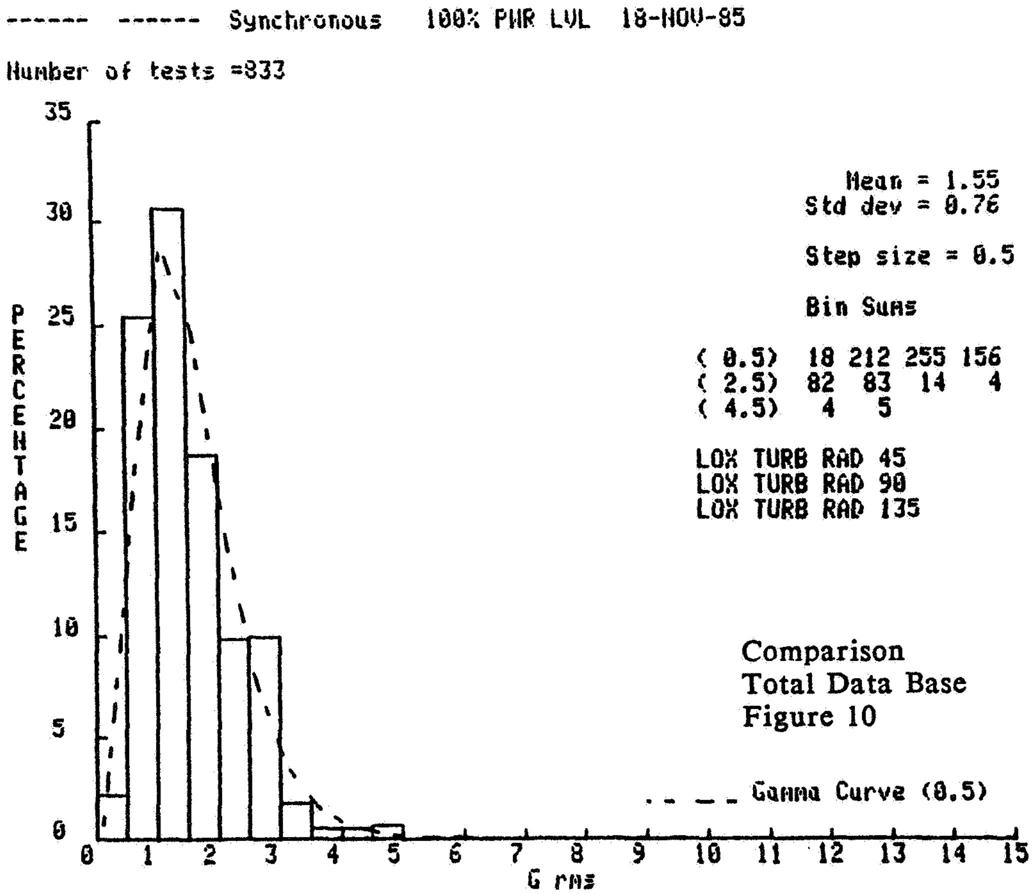


Figure 25. Probability Density HPOTP-TURB Normal Operation 100%

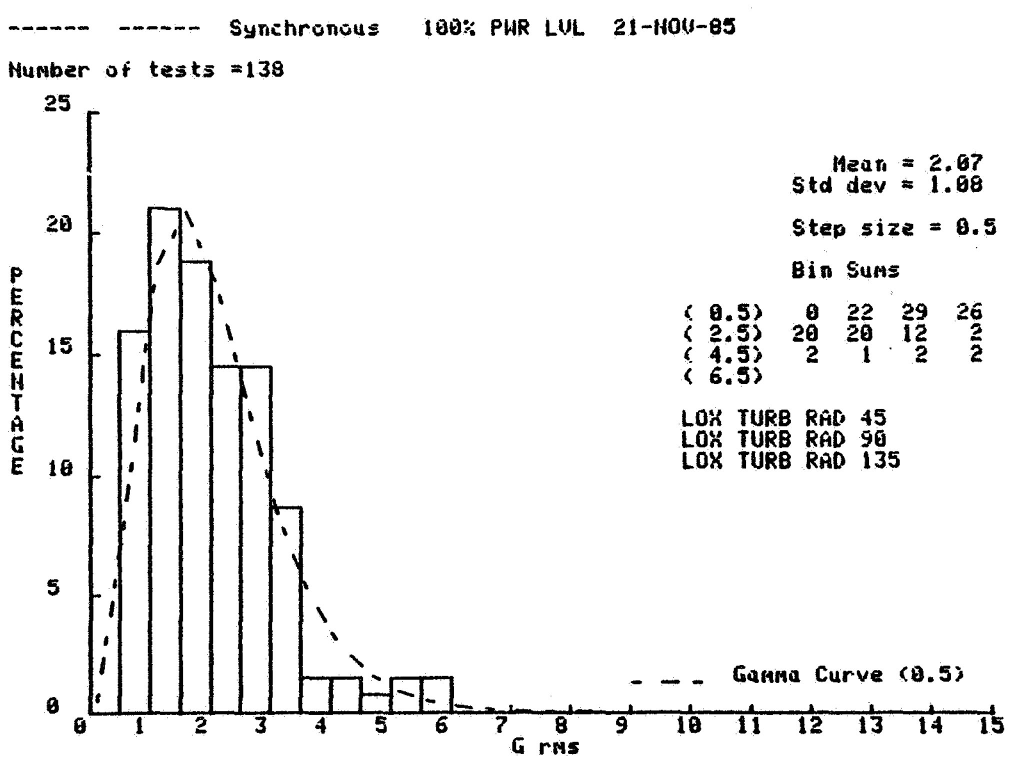


Figure 26. Probability Density HPOTP-TURB Six Main Impellers 100%

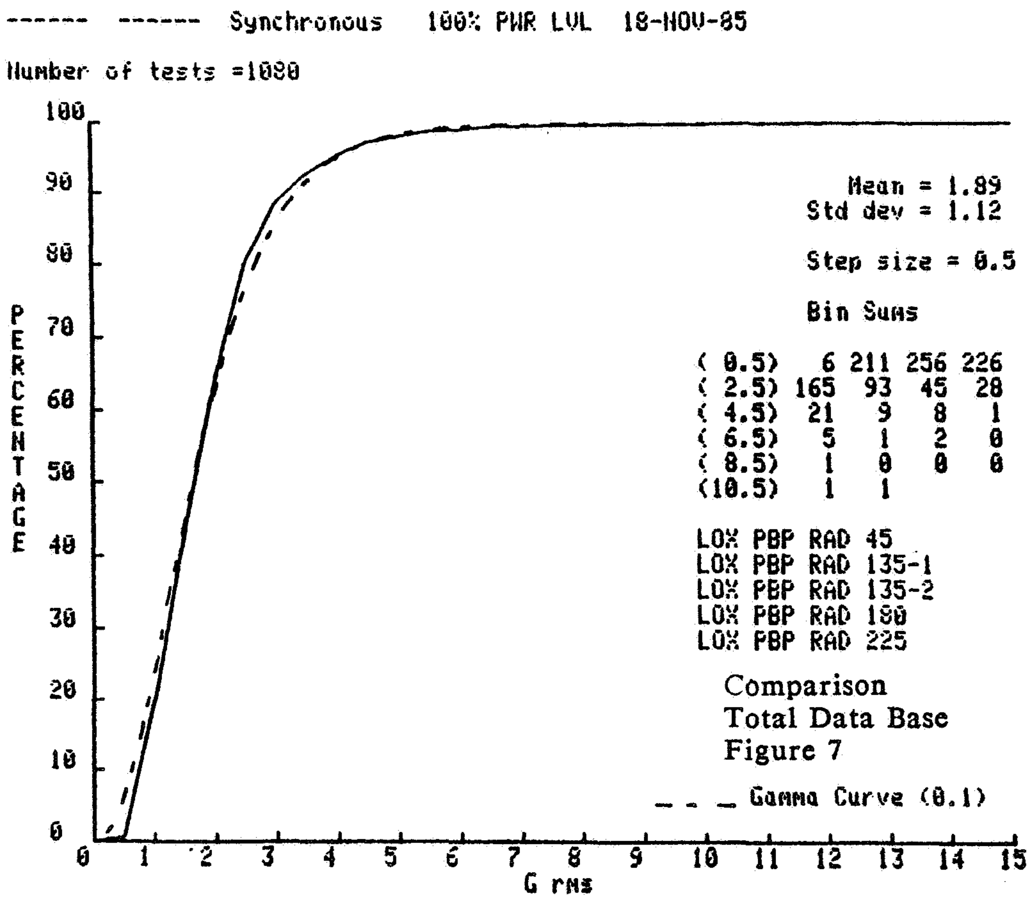


Figure 27. Cumulative Distribution HPOTP-PBP Normal Operation 100%

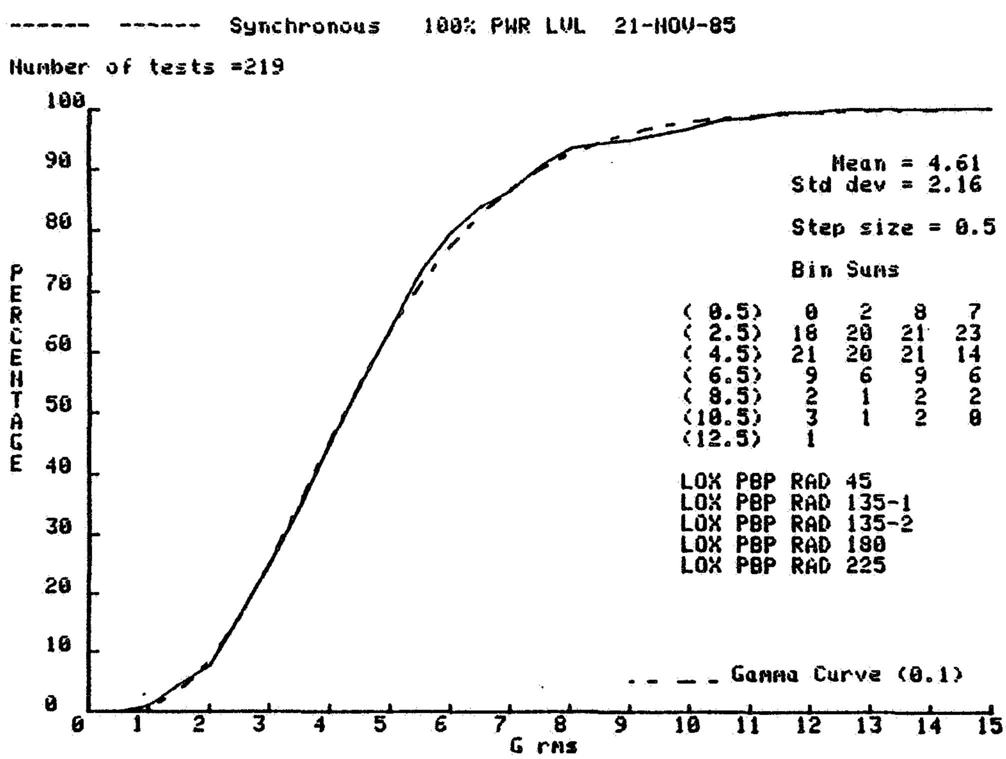


Figure 28. Cumulative Distribution HPOTP-PBP Six Main Impellers 100%

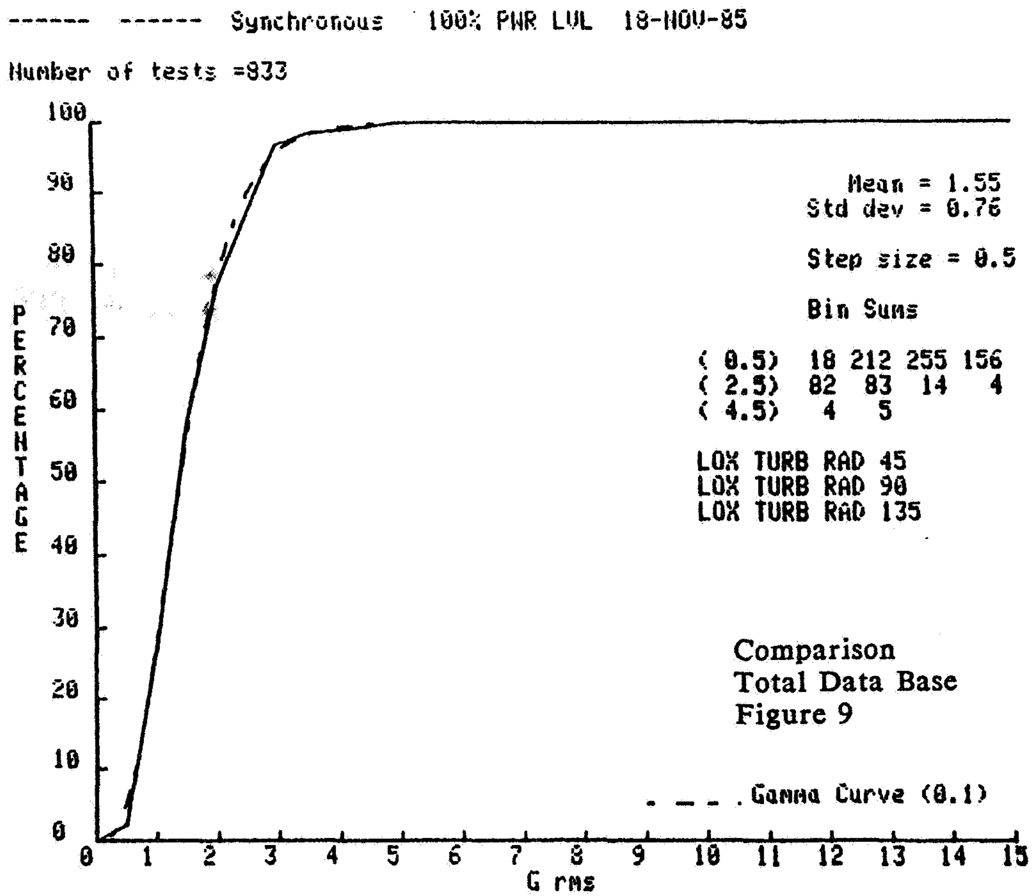


Figure 29. Cumulative Distribution HPOTP-TURB Normal Operation 100%

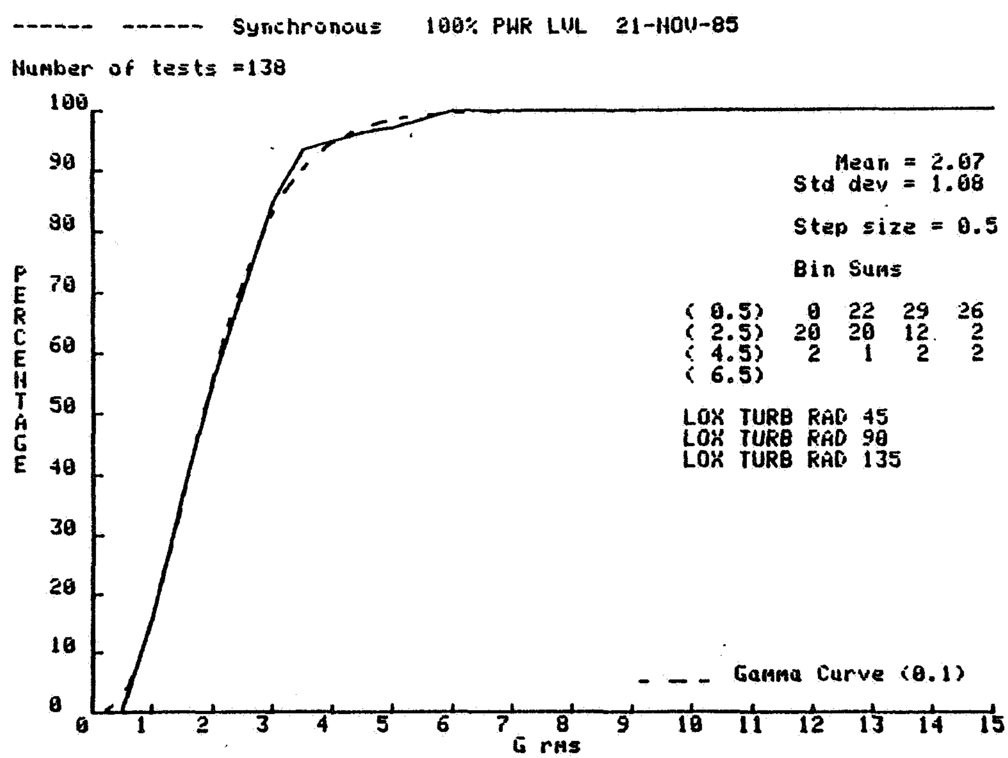


Figure 30. Cumulative Distribution HPOTP-TURB Six Main Impellers 100%

Normal HPOTP Operation 109%


```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1322-343,A1351-355,A1361-362,A1364-372,A1384-395,A1433-436,A14
45-493,A2193-261,A2267,A2272-276,A2286-372,A2377-381,A3125-152,A3154-168
,A3174-181,A3184-188,A3211-262,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

Six Main Impellers 109%

```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1344-349,A1358,A1374-381,A1398-399,A1401-405,A1443,A2268,A2277
-284,A2375-376,A3171,A3172,A3183,,A3190-191,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

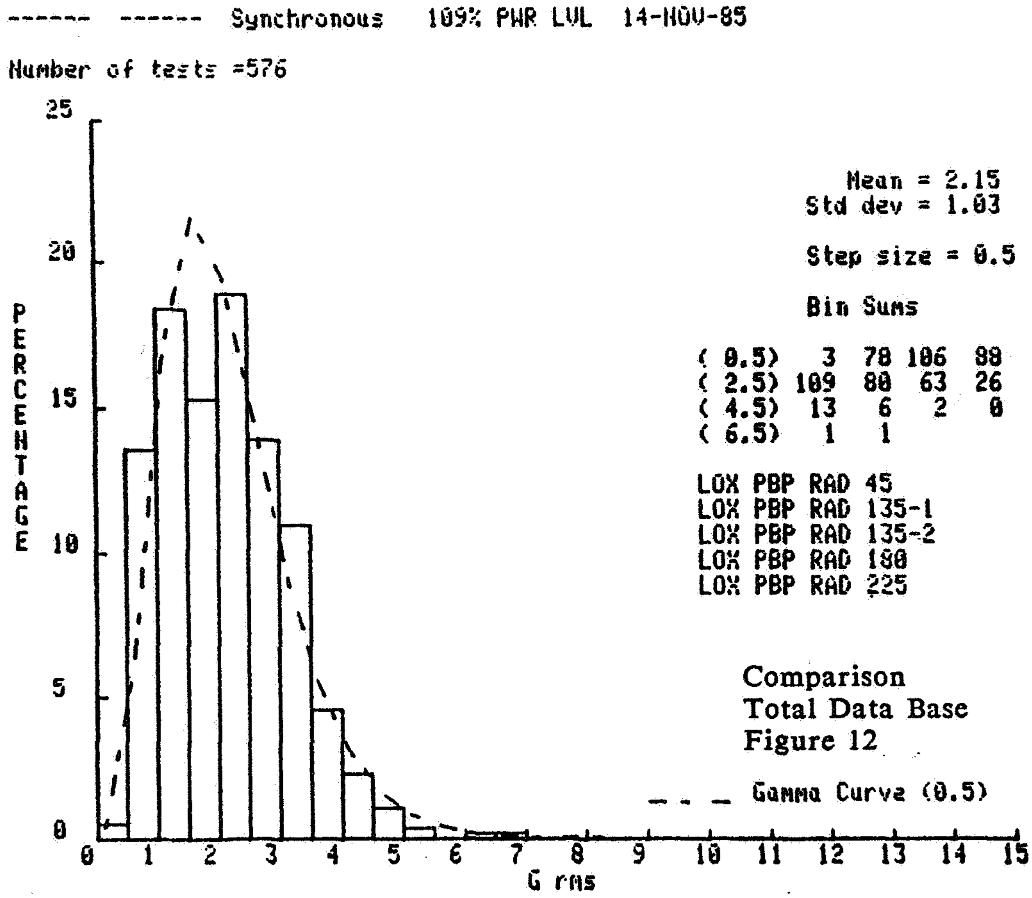


Figure 31. Probability Density HPOTP-PBP Normal Operation 109%

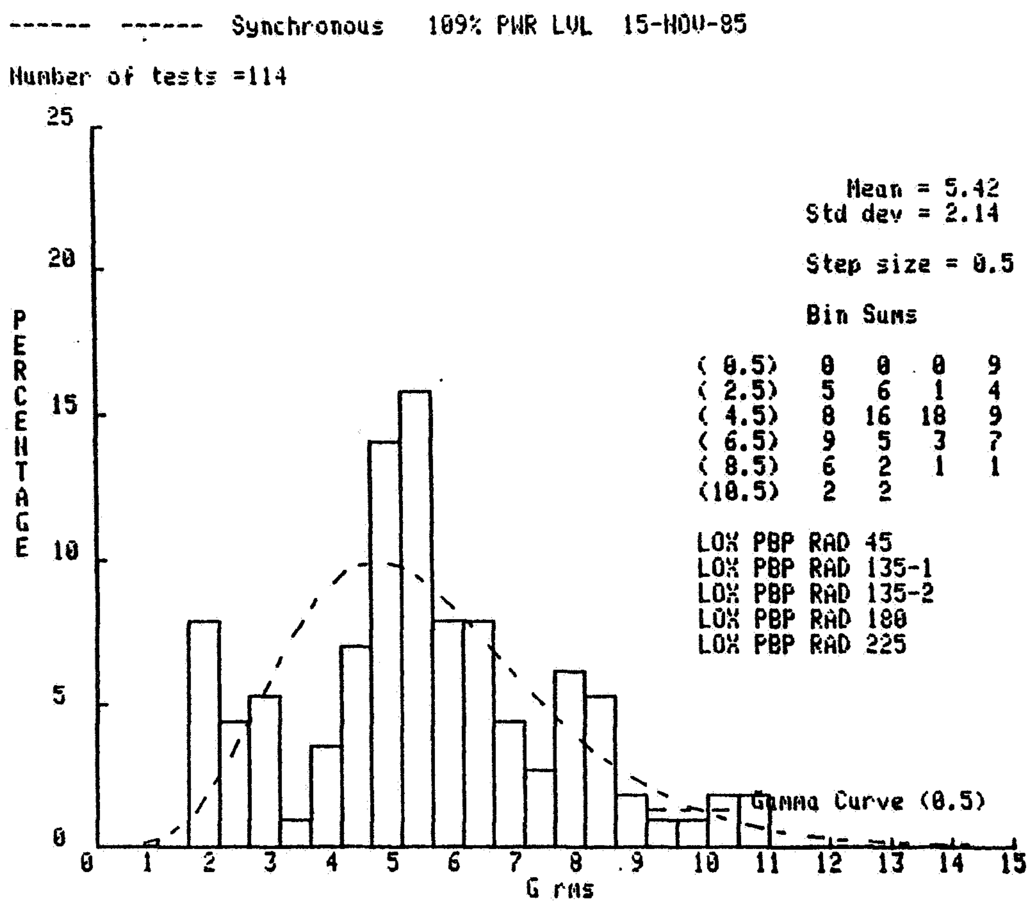


Figure 32. Probability Density HPOTP-PBP Six Main Impellers 109%

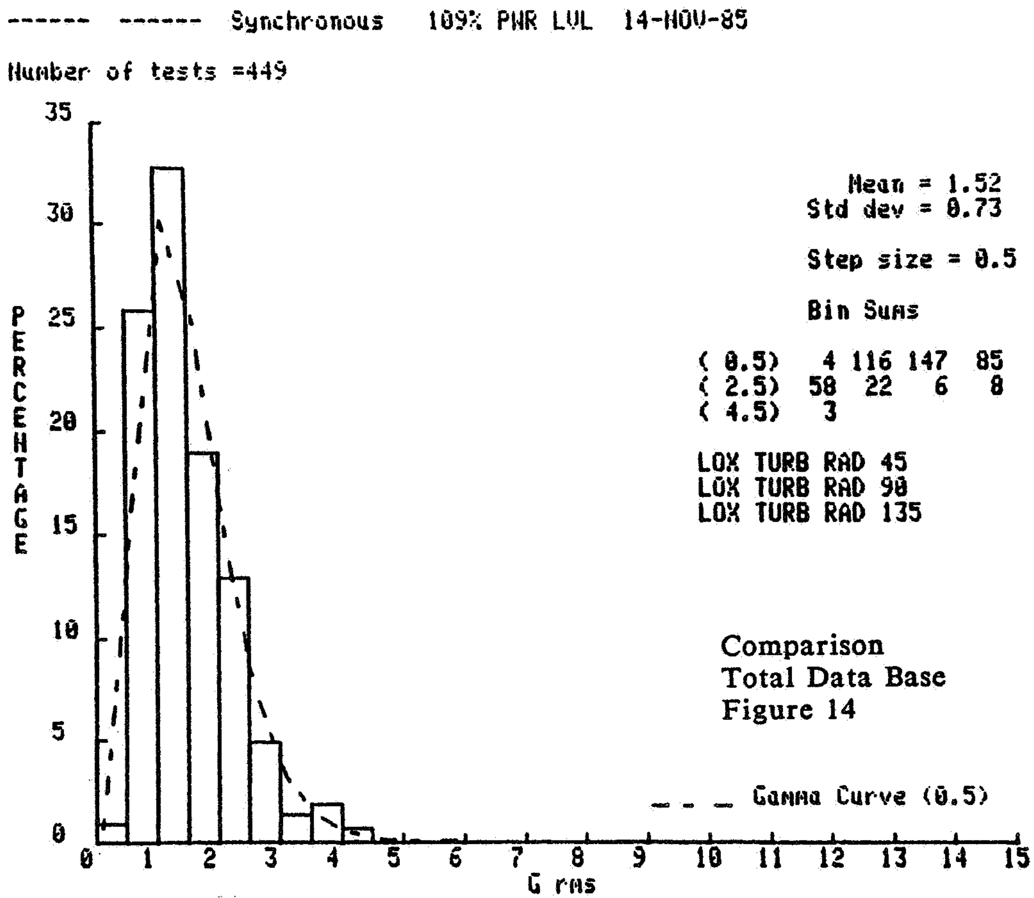


Figure 33. Probability Density HPOTP-TURB Normal Operation 109%

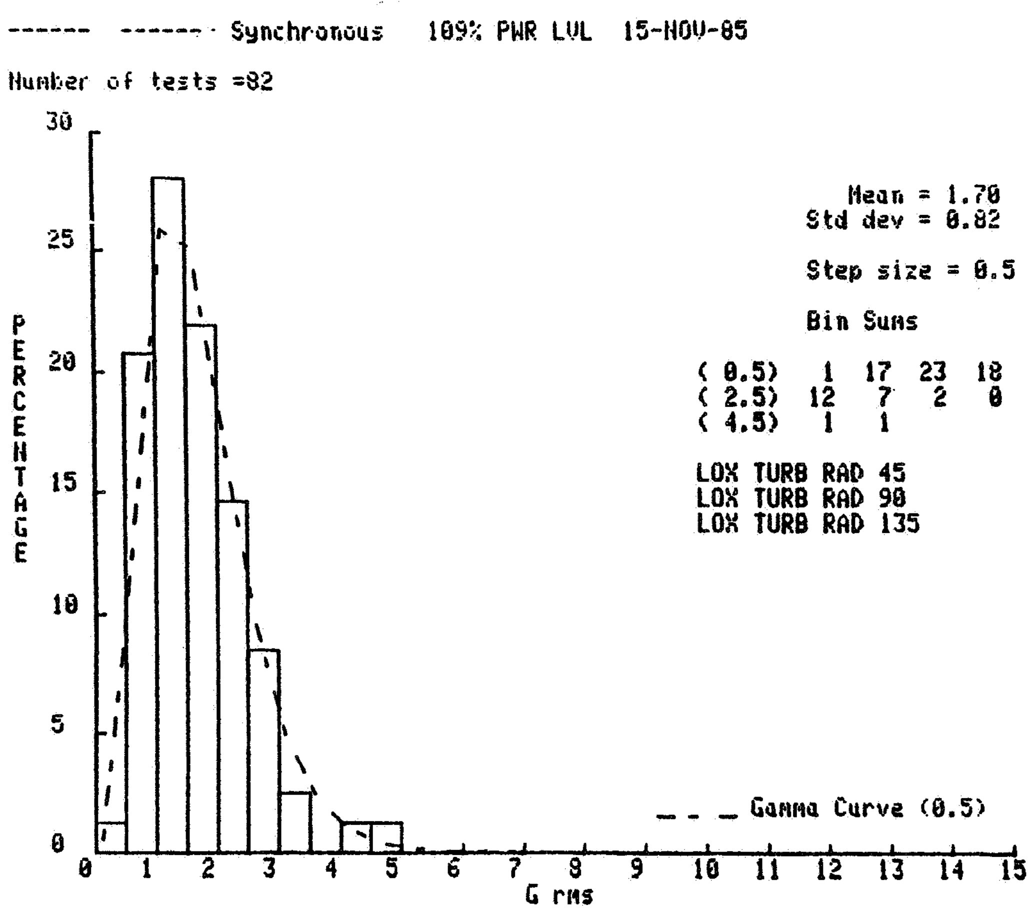


Figure 34. Probability Density HPOTP-PBP Six Main Impellers 109%

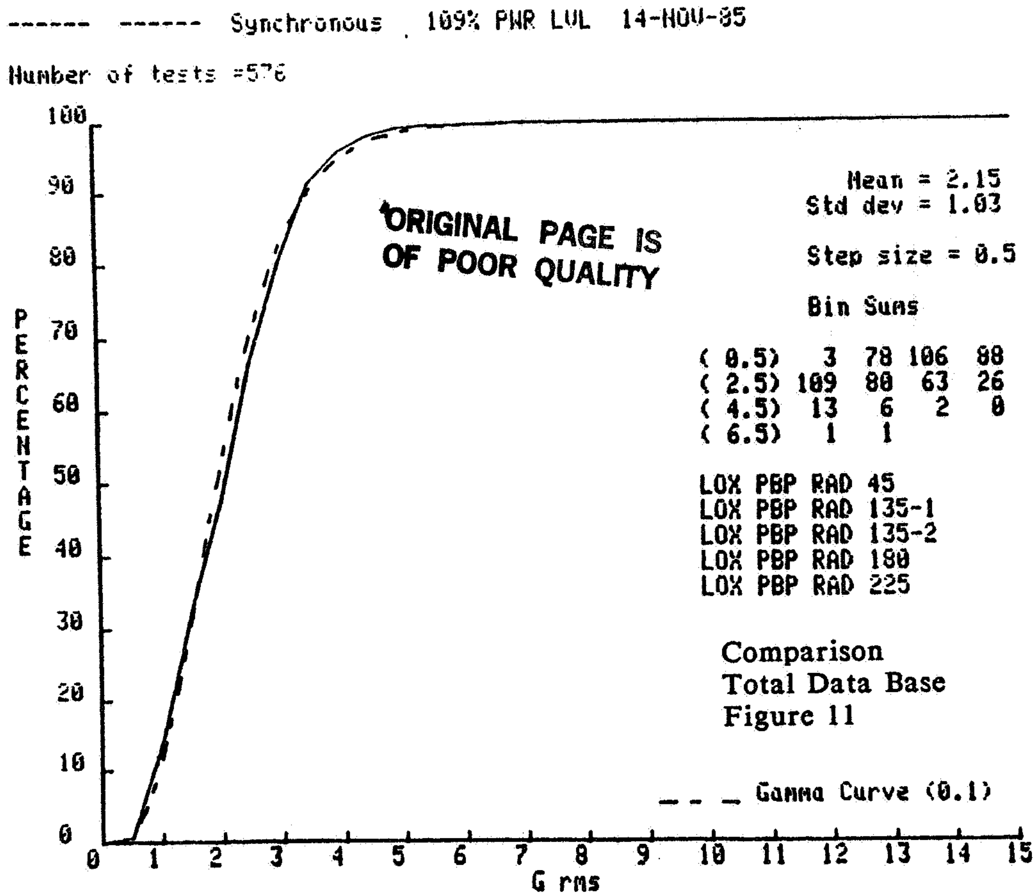


Figure 35. Cumulative Distribution HPOTP-PBP Normal Operation 109%

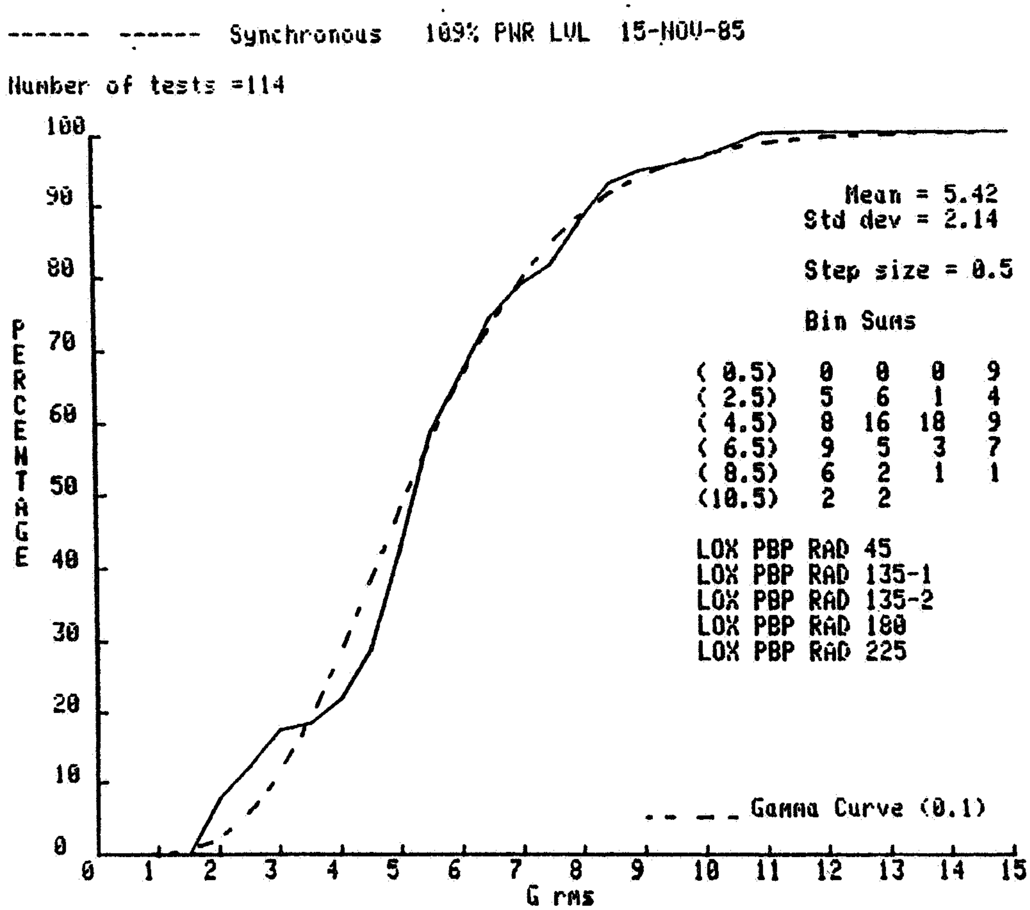


Figure 36. Cumulative Distribution HPOTP-PBP Six Main Impellers 109%

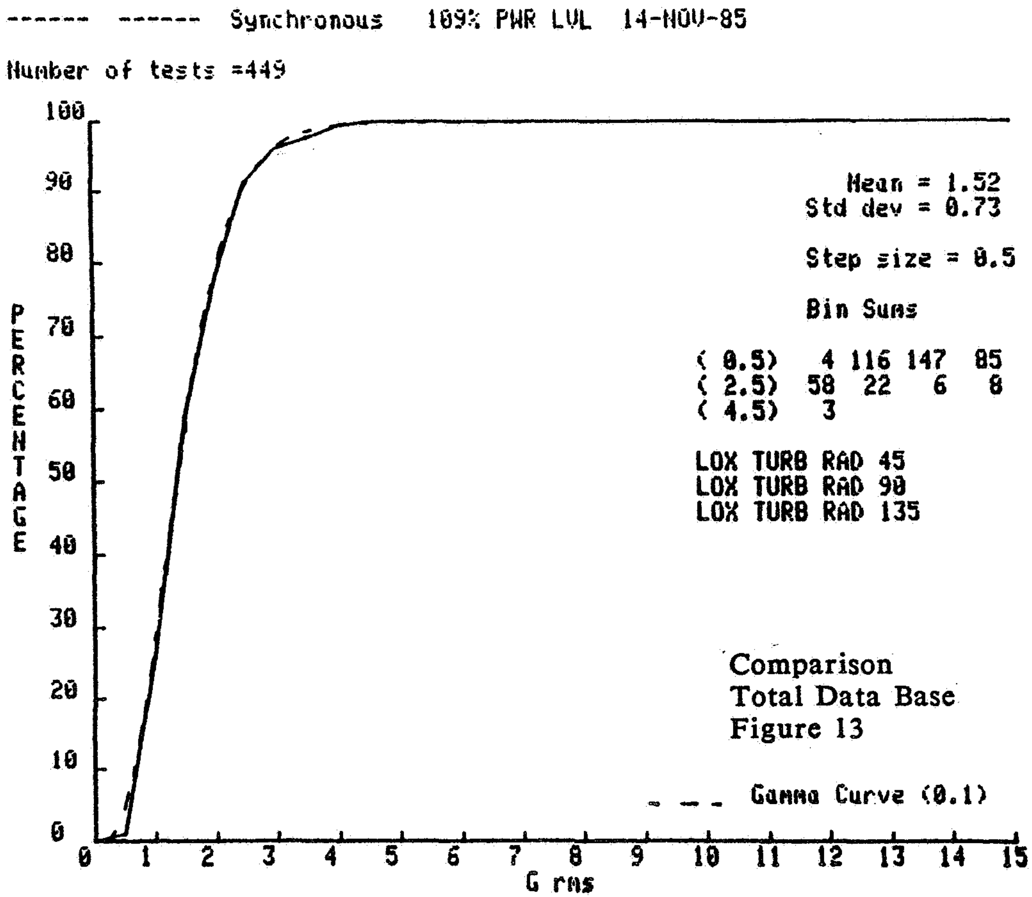


Figure 37. Cumulative Distribution HPOTP-TURB Normal Operation 109%

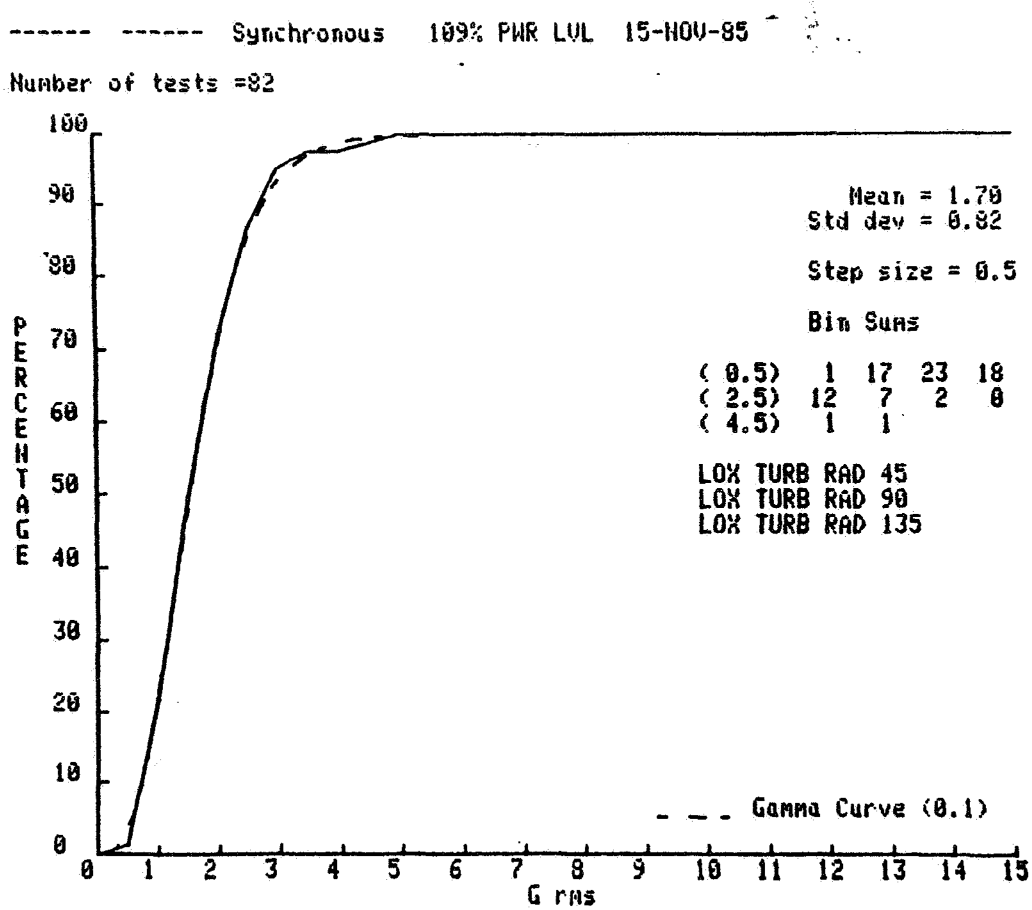


Figure 38. Cumulative Distribution HPOTP-TURB Six Main Impellers 109%

2.6 Random Selection of Tests

A random sample of 29 tests was selected, which is the number of tests in the six main impeller data sample, to evaluate the effect of sample size. The same analysis was used for this new data group and the results are shown in Figures 39 and 40. While it is recognized this method of analysis is not rigorous, it seems reasonable to assume a random selection should have followed a relative smooth continuous type of distribution unless the data is from two different data groups. The distribution is again bi-modal and presents additional evidence that the total data sample consists of two different data groups.

ORIGINAL PAGE IS
OF POOR QUALITY

Random Selection of 29 Tests

```
TESTS USED IN THIS ANALYSIS:

TEST #'S A1389-390,A1407,A1420,A1433,A1438,A1453,A1475,A1483,A1487,A2212
,A2296,A2311,A2314,A2326,A2331,A2340,A2363-365,A3181,A3193,A3199,A3201,A
3218,A3221-222,A3227,A3257,

ENTER...1) LIST STANDARD TABLE
        2) PLOT PROBABILITY DISTRIBUTION
        3) PLOT PROBABILITY DENSITY
        4) SELECT A NEW SET OF TESTS
        5) SELECT NEW DATA TYPE AND PWRLVL
        6) RETURN TO MAIN
```

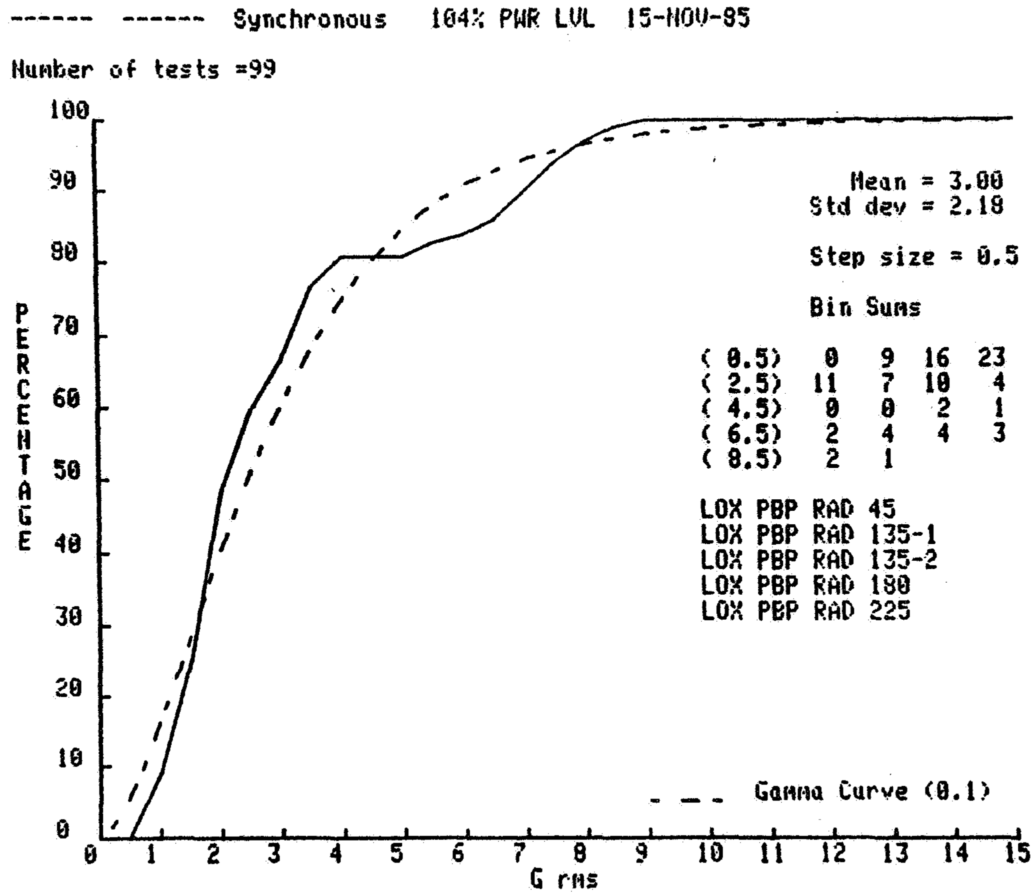


Figure 39. Cumulative Distribution HPOTP-PBP Random Selection of 29 Tests 104%

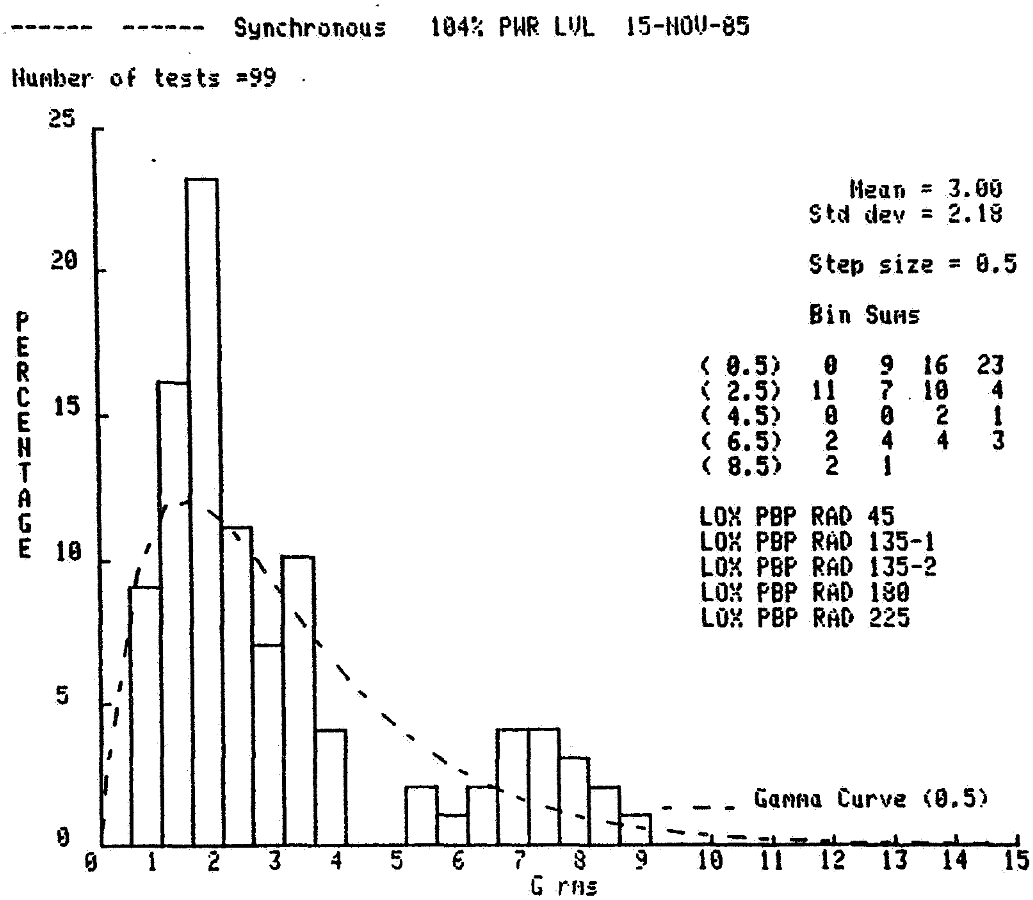


Figure 40. Probability Density HPOTP-PBP Random Selection of 29 Tests 104%

2.7 Vibration Test History of the Six Main Impellers

To complete this analysis, the synchronous spatial average vibration test history of the six main impellers is plotted. In the original study the data was hand plotted, and later incorporated as a routine in the MSFC Diagnostic Data Base Program. The output is shown in Figures 41 to 46. Listed below are the main impeller serial numbers, HPOTP serial number, last test and date of test.

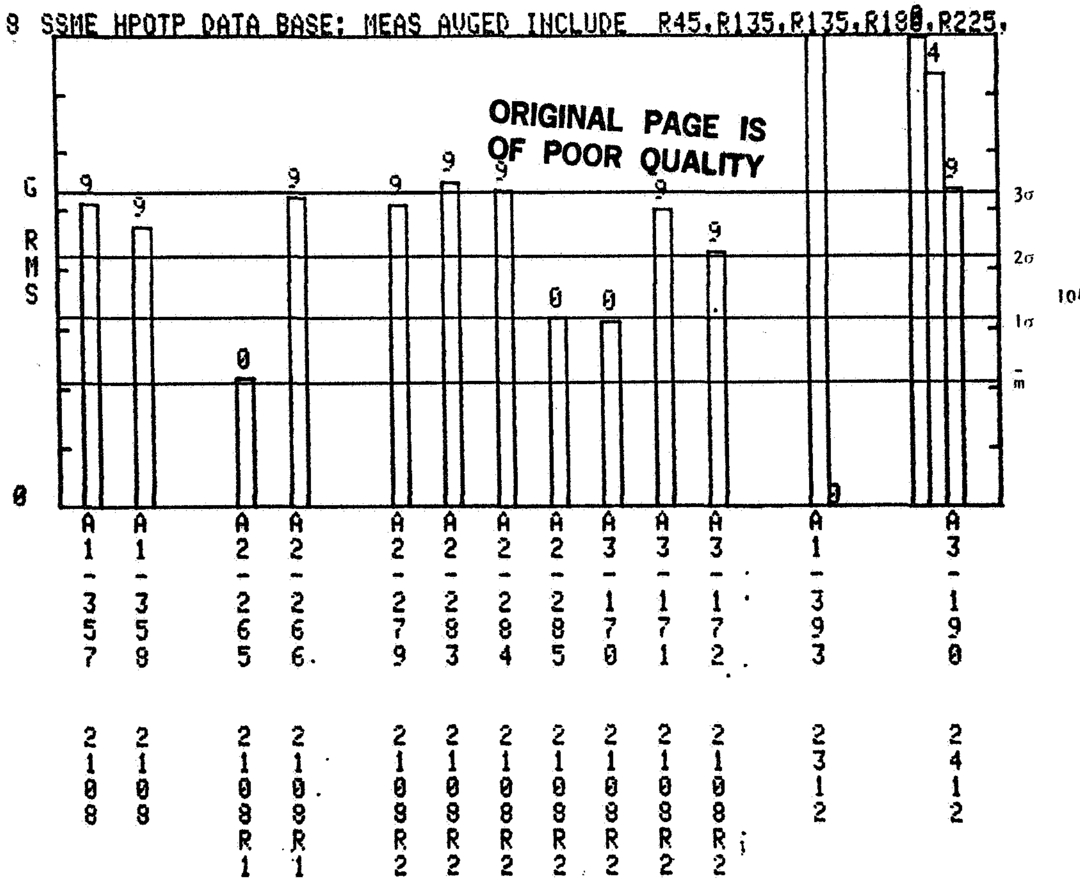
Main Impeller S/N	HPOTP #	Last Test	Date
2427800	2412	A3-207	7-21-83
3134124	2311R1	A1-405	2-4-83
3334446	2208R1	A1-432	1-4-84
3135444	0210R2	A3-192	3-2-83
7326066	0307	A2-376	11-11-83
7363708	9111R1	A3-191	2-12-83

It is beyond the scope of this study to fully investigate the variation in synchronous vibration levels from test to test, pump build to pump build or verify the six main impellers were the sole contributor to the bi-modal distribution of the HPOTP synchronous vibration data. However, since the original study only main impeller S/N 7326708, HPOTP #0307, Test A2-375 and A2-376 (Figure 46) has deviated from the pattern of all the identified main impellers being associated with abnormal synchronous vibration levels. For reference, the mean, 1σ, 2σ, and 3σ vibration levels for normal turbopump operation are as follows.

HPOTP PBP RAD Spatial Average Synchronous

	100%	104%	109%
Mean	1.89 Grms	2.09 Grms	2.15 Grms
Std Dev	1.12 Grms	1.05 Grms	1.03 Grms
Mean + 1 σ	3.01 Grms	3.14 Grms	3.18 Grms
Mean + 2 σ	4.13 Grms	4.19 Grms	4.21 Grms
Mean + 3 σ	5.25 Grms	5.24 Grms	5.24 Grms

The vibration levels for 104% power level are shown on each plot to illustrate the deviation from the expected normal operation value and relationship to the sigma levels.



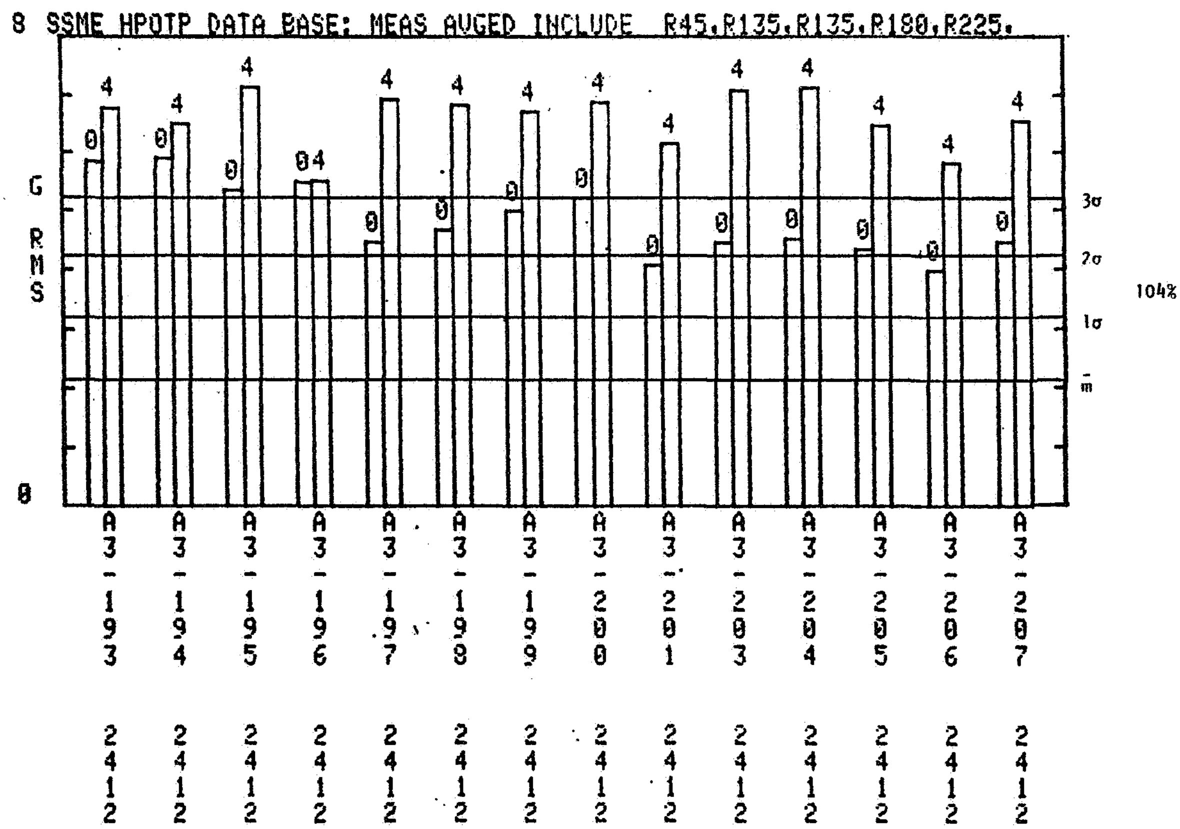


Figure 41. Synchronous Vibration Test History, Spatial Average PBP, Impeller S/N 2427800

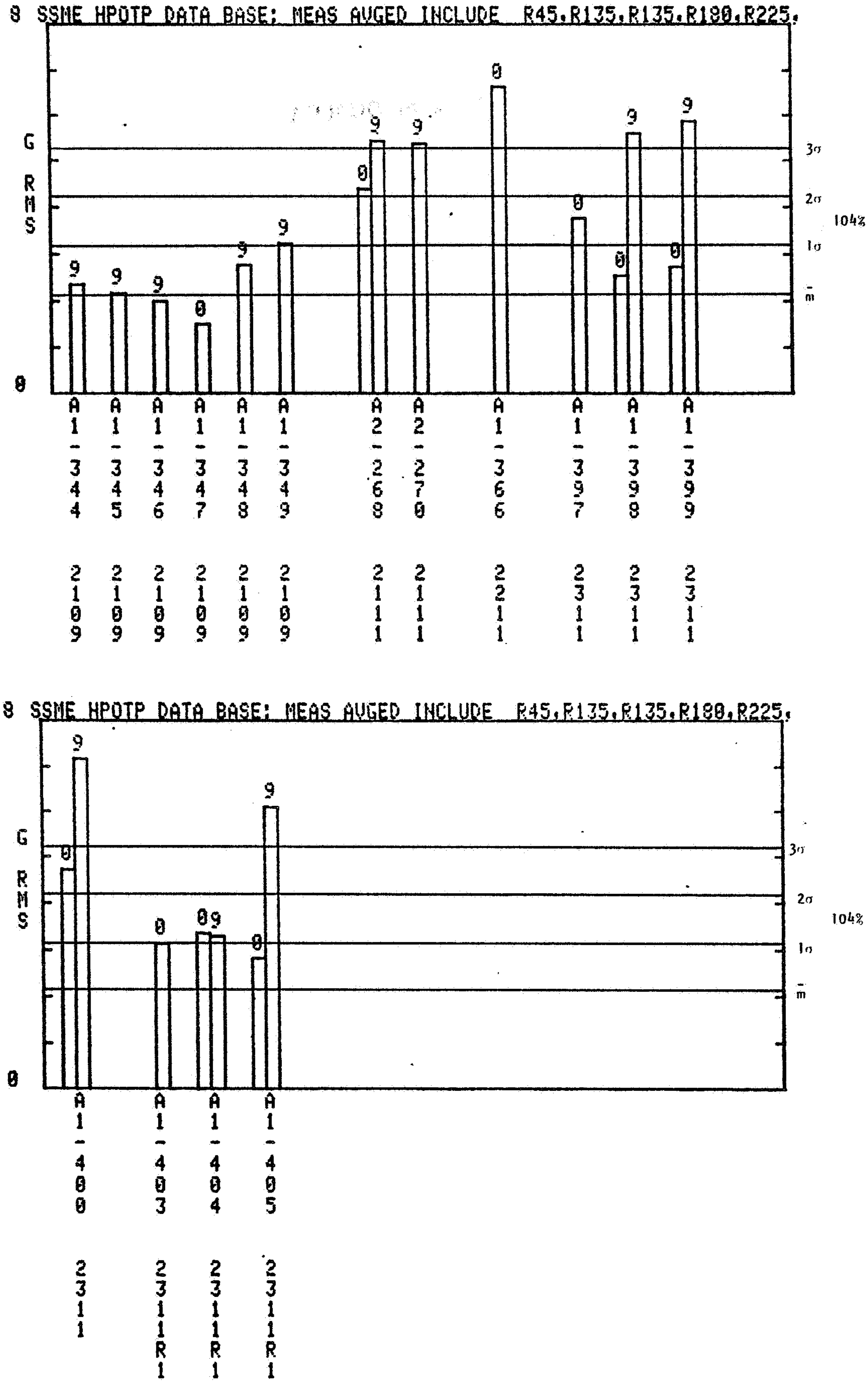
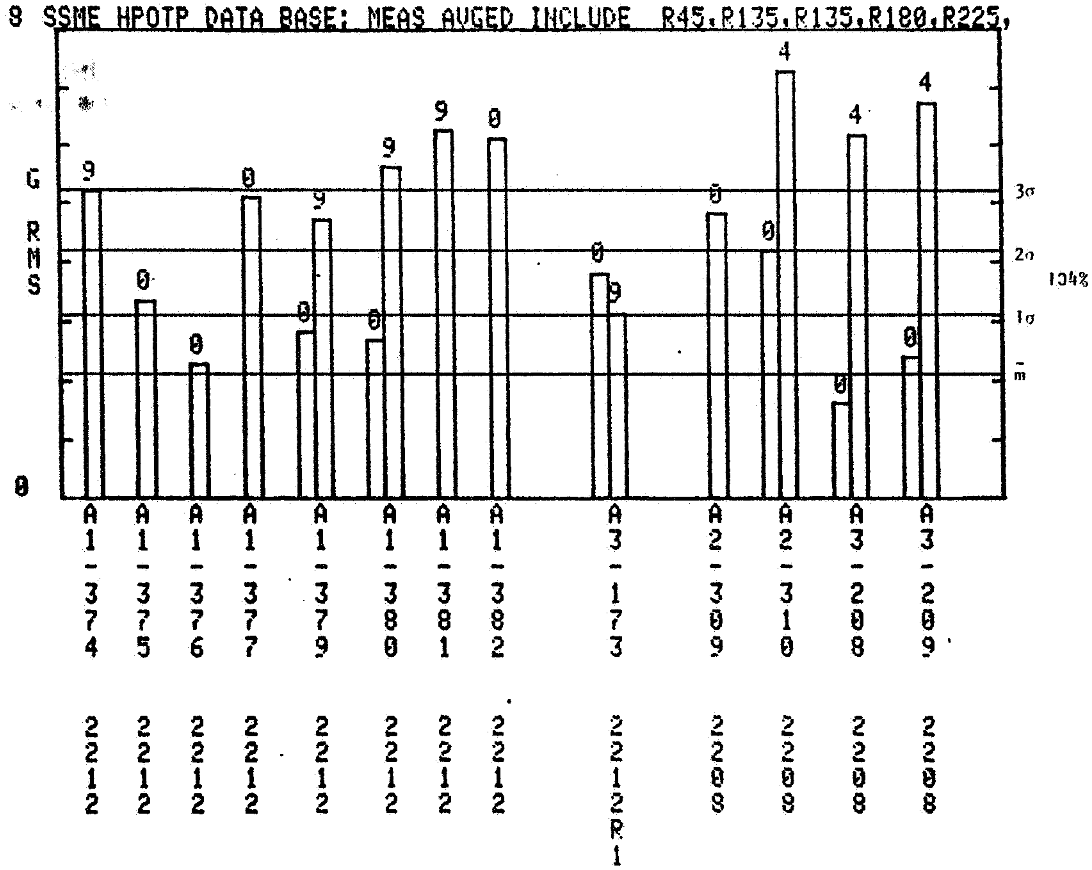


Figure 42. Synchronous Vibration Test History,
Spatial Average PBP, Impeller S/N 3134124



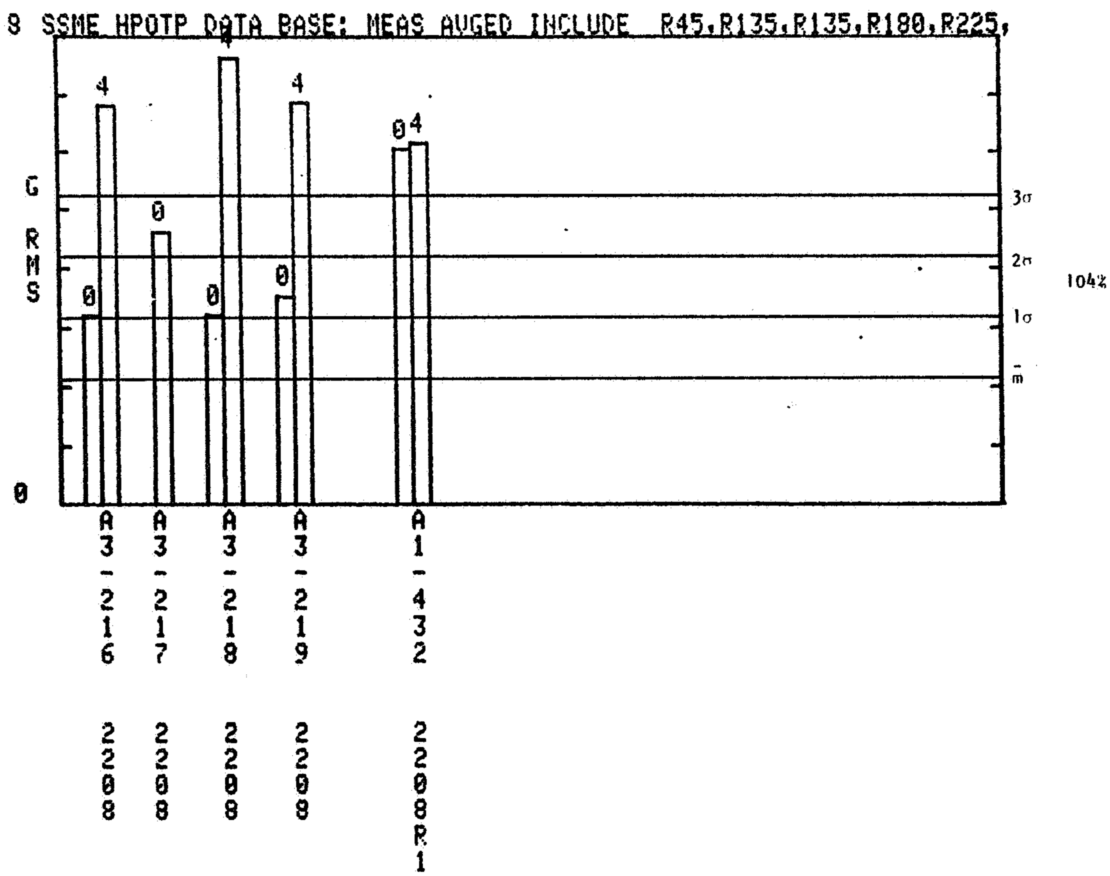


Figure 43. Synchronous Vibration Test History, Spatial Average PBP, Impeller S/N 3134446

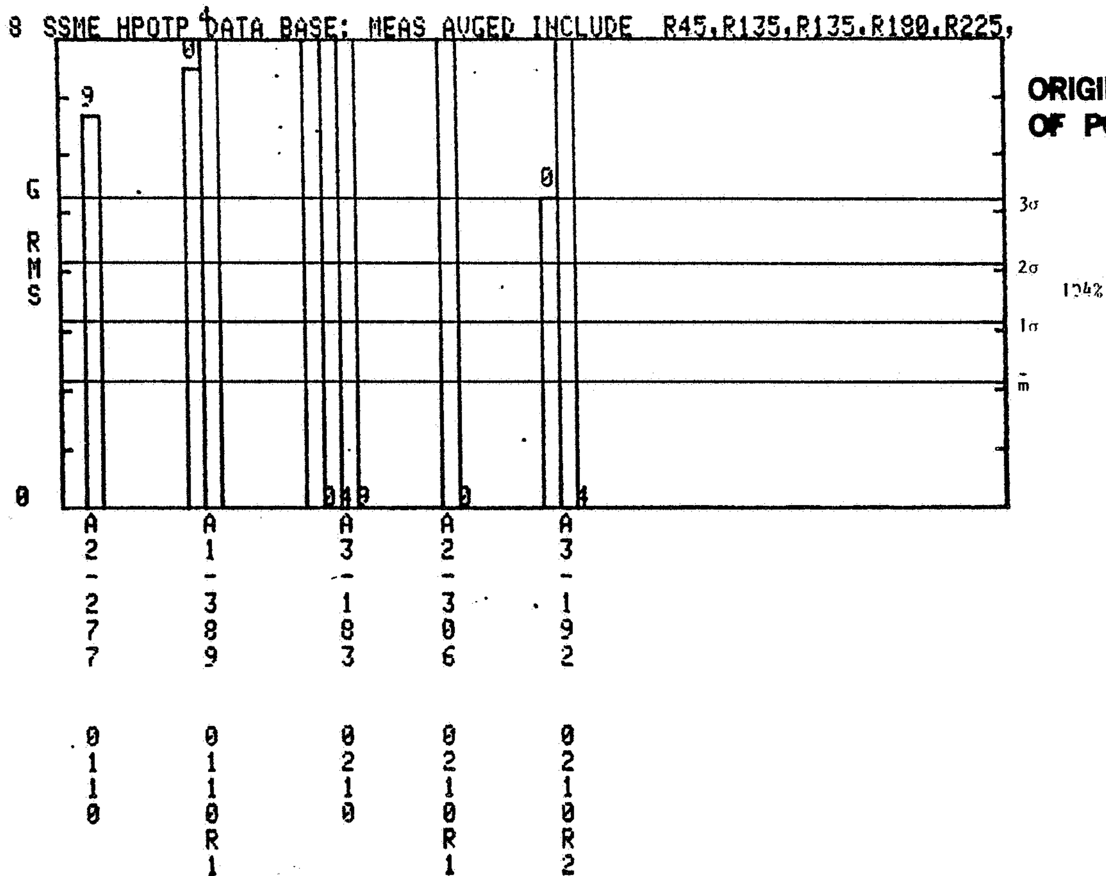


Figure 44. Synchronous Vibration Test History, Spatial Average PBP, Impeller S/N 3135444

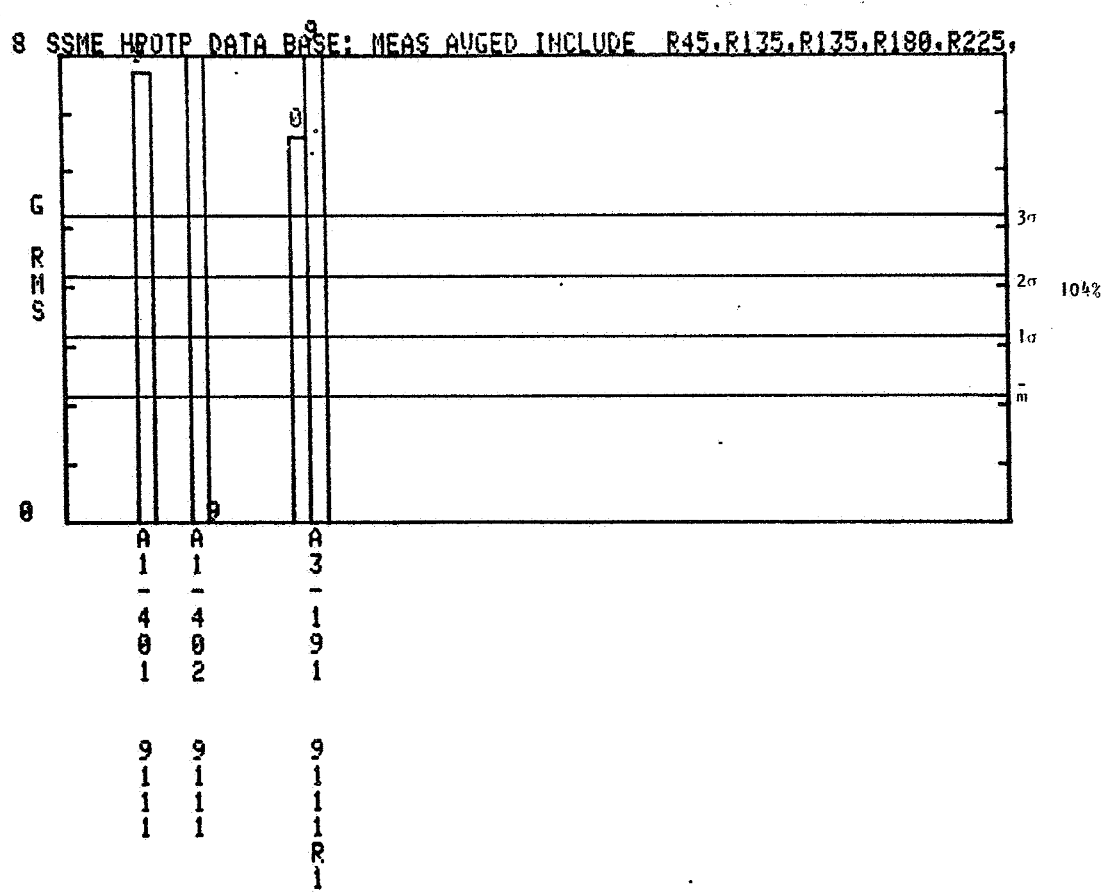
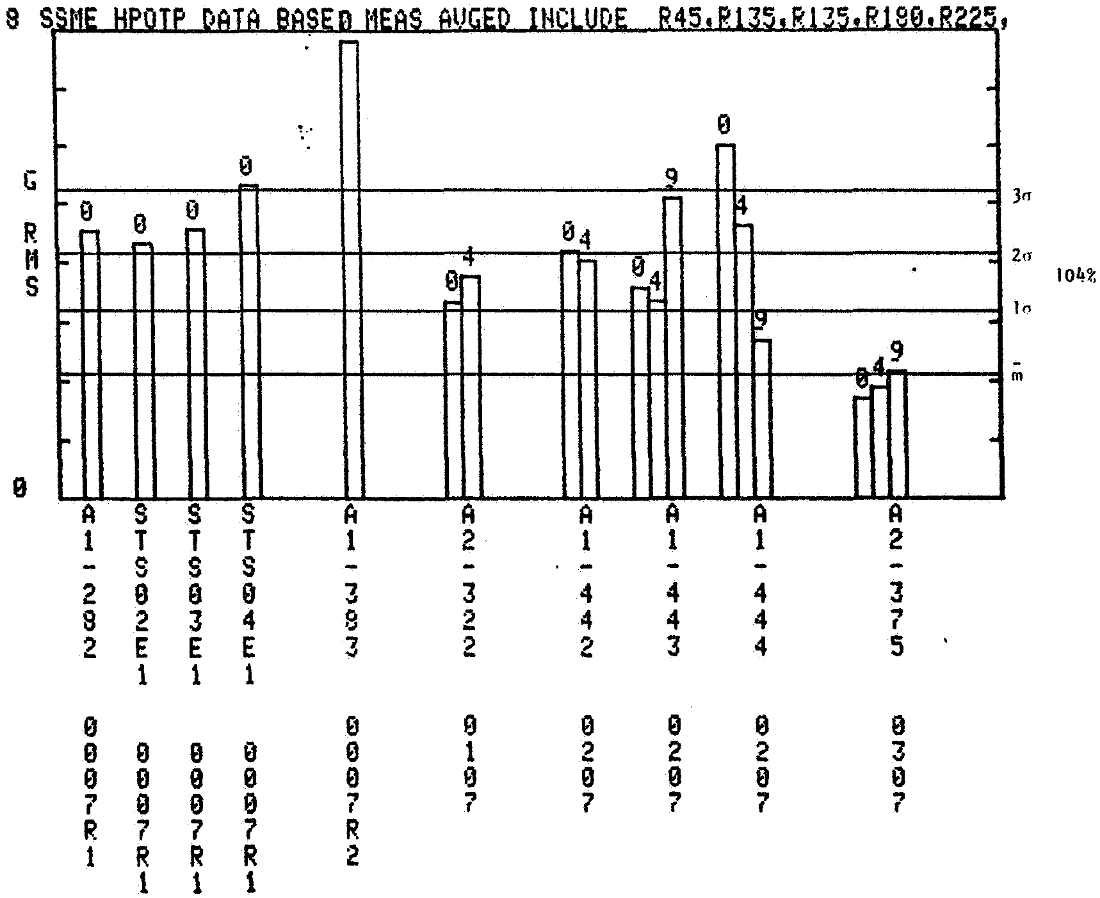


Figure 45. Synchronous Vibration Test History, Spatial Average PBP, Impeller S/N 7363066



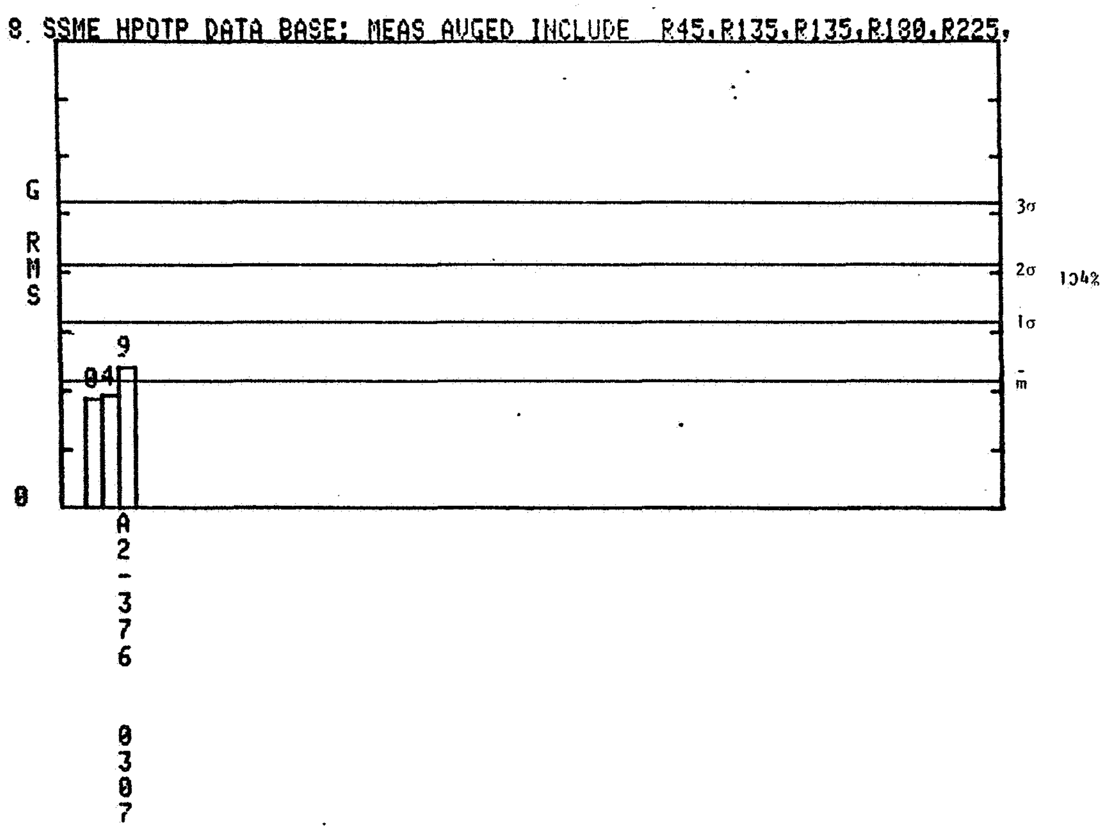


Figure 46. Synchronous Vibration Test History, Spatial Average PBP, Impeller S/N 7326708